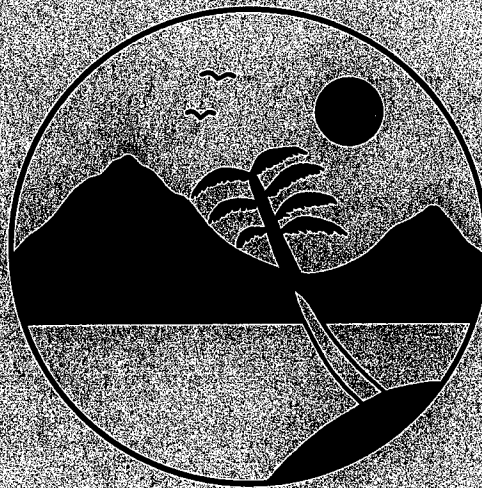


# WATER, SEDIMENTS AND ECOLOGY OF THE MANGROVE LAGOON AND BENNER BAY, ST. THOMAS



Final Report

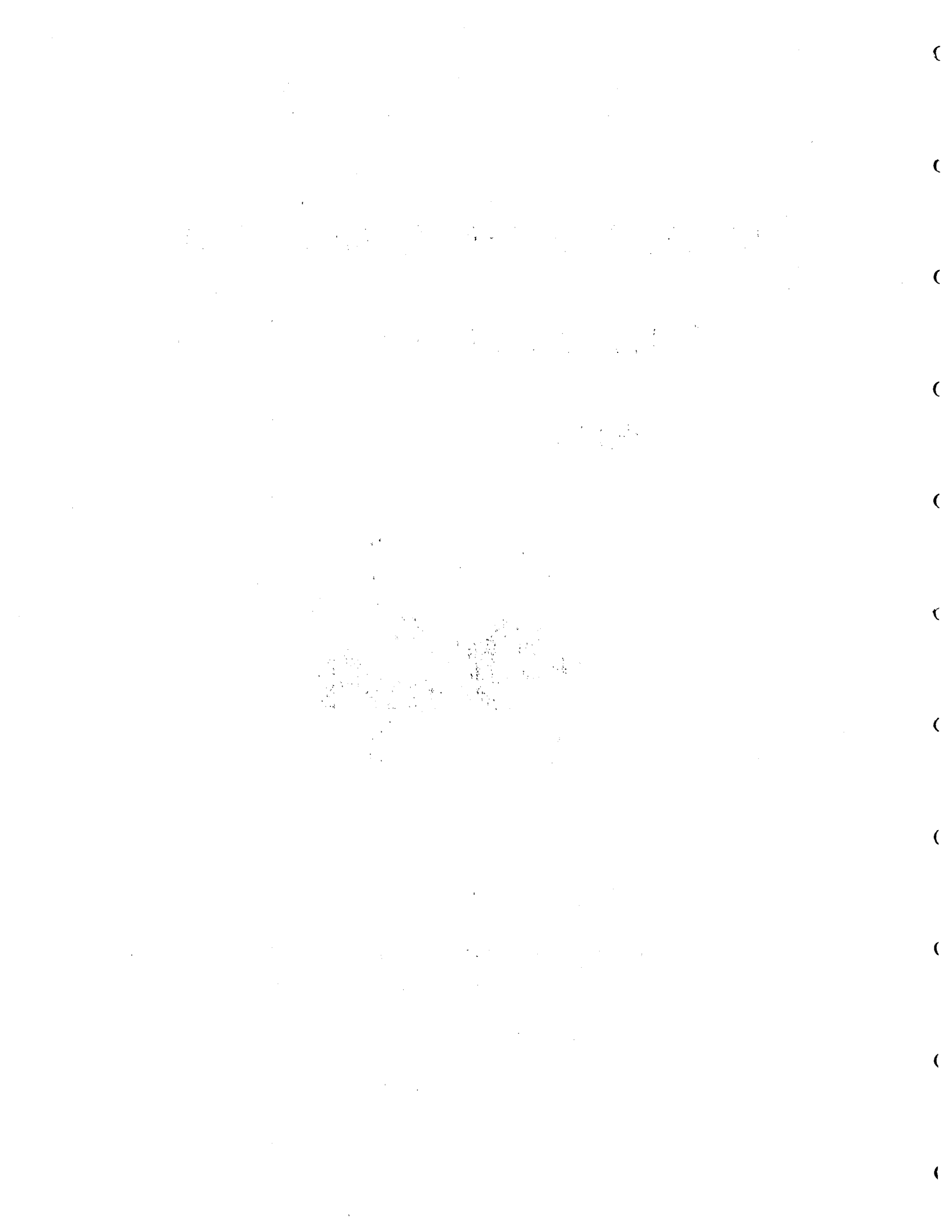
Prepared For: Department of Conservation and Cultural Affairs  
Division of Natural Resources Management

By: Island Resources Foundation St. Thomas, Virgin Islands

October, 1977

**OFFICE COPY**

ISLAND RESOURCES  
FOUNDATION  
1718 P STREET, N.W., SUITE T-4  
WASHINGTON, DC 20036  
(202) 265-9712



A Final Contract Report Prepared Under Contract #PC-CCA-9-77

DEPARTMENT OF CONSERVATION AND CULTURAL AFFAIRS  
DIVISION OF NATURAL RESOURCES MANAGEMENT  
GOVERNMENT OF THE U.S. VIRGIN ISLANDS

WATER, SEDIMENTS AND ECOLOGY  
OF THE MANGROVE LAGOON AND BENNER BAY,  
ST. THOMAS

by

Maynard Nichols and Edward Towle

with

Gilbert Cintron, David Grigg, Robert Huggett, David Olsen,  
William Rainey, Edwin Rosenberg, Galen Thompson and Richard Trotman

Submitted by:

Island Resources Foundation  
Box 4187, St. Thomas  
U.S. Virgin Islands

Dr. Edward L. Towle, Director

October 1977



## ABSTRACT

The mangrove shores, cays, ponds and waters of the Mangrove Lagoon and Benner Bay, St. Thomas are a natural resource of special value. The region once had clear water, moderate water depth, thriving mangrove stands and luxuriant grass beds. Today, after 8 years of accelerated development, the region has markedly changed. The lagoon is polluted and shoaled; mangroves are dying and grass beds are largely destroyed. In turn, birds, fish and shellfish are deprived of their food and nursery grounds. Only a small zone, Bovoni and Patricia Cays and Cas Entrance, remains intact.

The most important man-induced stresses affecting the region are: pollution, sedimentation and development of the waterfront and watershed. Pollution of the bay is caused by sewage from boats and diffuse sources in the watershed and on the waterfront. Pollution of the lagoon is caused by nutrient-rich runoff from Turpentine Run and by an overloaded, malfunctioning and obsolete sewage treatment plant.

The excess supply of nutrients combined with weak water circulation in the lagoon, lead to eutrophication (over-fertilization) and rapid growth of phytoplankton. In turn, the near-bed oxygen content is depressed (<50 percent saturation) and the water is turbid (>2 JTU). By screening out light, turbidity has reduced grass beds to a small area of shoals; less than 10 percent of the beds remain. They are survived by extensive growth of benthic algae Halimeda, and by the seagrass Halophila which lives on black mud. Most shellfish (bivalves) are reduced in number, while polychaetes (Sabellid worms) and benthic jelly fish (Cassiopea) have invaded a wide area of inner zones. The lagoon head, mouth of Turpentine Run and eastern Benner Bay are devoid of benthic life. The greatest impact of pollution is felt in inner zones close to sewage sources where circulation and exchange is least.

The calcareous algae, Halimeda, supply much sediment to the central lagoon while land-borne silt and clay derived from the watershed supplies mud to the inner lagoon floor, tidal flats and salt ponds. Infilling from the land has been accelerated by uncontrolled waste disposal, landfill and strip-ping of the soil, especially on government property between the racetrack and the municipal dump.

As a consequence of marginal infilling the tidal volume is reduced and the amount of water and biota exchanged between ponds and the lagoon is inhibited. Mangroves suffer both from the restricted tidal drainage and direct burial.

Water quality is degraded by anoxic sediments in backwaters, by turbidity released from erodable landfill and by phytoplankton growth. In brief, a number of small changes have produced large effects.

The lagoon and bay appear doomed as a natural system. With its demise, a significant natural and recreational resource for Virgin Islanders will be lost. Only a prompt and major initiative can stall the decline. This report provides a scientific background for improving the environment and suggests management practices leading to the best achievable condition.

# CONTENTS

|                                                         | Page No. |
|---------------------------------------------------------|----------|
| Abstract                                                | i        |
| 1. Introduction                                         | 1        |
| 2. Study Objectives                                     | 4        |
| 3. Scope and Previous Studies                           | 7        |
| 4. Methods and Procedures                               | 8        |
| Station Locations                                       | 8        |
| Instrumentation and Procedures                          | 10       |
| Observational Period and Data Acquired                  | 14       |
| Mangrove Studies                                        | 15       |
| Benthic Biota                                           | 16       |
| 5. Description of the Lagoon System                     | 18       |
| Aerial Photo Evaluation                                 | 23       |
| Bathymetry                                              | 28       |
| Bathymetry Changes                                      | 33       |
| 6. Watershed and Drainage                               | 37       |
| 7. Geologic Conditions                                  | 47       |
| Depositional Units                                      | 49       |
| Stratigraphic Sequence                                  | 53       |
| Radiocarbon Dating                                      | 55       |
| Geologic Development                                    | 59       |
| 8. Environmental Conditions                             | 62       |
| Waves                                                   | 62       |
| Tides                                                   | 65       |
| Tidal Boundary Demarcation                              | 68       |
| Circulation                                             | 70       |
| Water Quality                                           | 77       |
| Productivity                                            | 89       |
| Bottom Sediments                                        | 93       |
| Sediment Chemistry                                      | 96       |
| 9. Biological Conditions                                | 100      |
| Mangrove Studies                                        | 100      |
| Benthic Biota                                           | 115      |
| 10. Improving the Benner Bay Entrance Channel           | 136      |
| 11. Summary of Scientific Findings & Their Significance | 142      |
| 12. Prospect                                            | 148      |
| 13. Recommendations                                     | 149      |
| 14. References                                          | 153      |
| 15. Acknowledgements                                    | 155      |
| Appendix I and II                                       | 156, 159 |



# WATER, SEDIMENTS AND ECOLOGY OF THE MANGROVE LAGOON AND BENNER BAY, ST. THOMAS

## 1. Introduction

The south coast of St. Thomas is endowed with an attractive mangrove lagoon and bay of exceptional natural value. Its water and grass beds formerly provided a rich nursery area for fish and a productive habitat for benthic biota. Its mangrove fringed shores are a natural buffer against shore erosion, floods and hurricane waves. Its configuration provides a protective anchorage for boats and its adjoining hillsides are popular residential areas for Virgin Islanders. The area is filled with scenic contrasts, manglar islands, rocky cliffs, ponds and panoramic ridgelines. Its diverse complex of natural communities provides a recreational and educational opportunity for Virgin Islanders. These combinations of attributes have attracted so many people in recent years that the very elements that attracted them to the area are being degraded.

Traditional uses of the lagoon have included fishing, crabbing, clamming, cutting mangrove wood for charcoal and boat timbers and protected anchorage for boats, particularly during hurricanes. From 1968 to 1976, development of the shores has proceeded virtually unchecked. Upland slopes and flood plains were bulldozed for residential sites, mangroves were cut and buried to create marinas, docks, a sewage plant, roads and a racetrack. More people and more boats (Figure 1) created a need for facilities, i.e., more fresh water, more power, more parking, more docks, and sewers, which in turn created more pollution. As pressures for

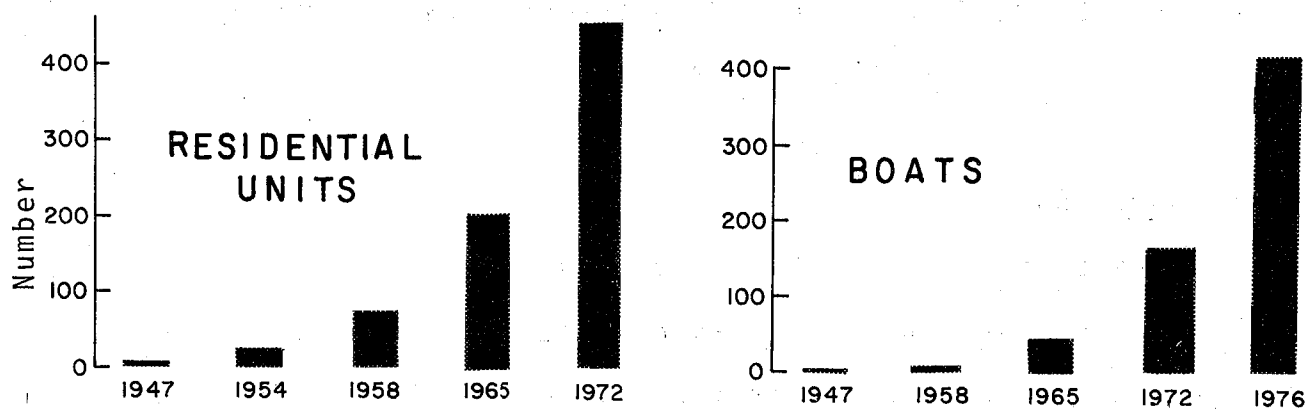


Figure 1. Time trends in the number of residential units and boats in the Mangrove Lagoon-Benner Bay region.

development mounted, more environmental problems were created and the lagoon's most useful environmental values were threatened. Among the stresses and impacts impinging on or present in the lagoon in 1976-77 are:

- Sewage pollution from anchored boats, the Nadir sewage treatment plant, local septic tanks and shore establishments.
- Release of toxic trace metals from the municipal dump, boat yards and local debris scattered around lagoon margins and watershed.
- Discharge of petroleum products, i.e., oil, gasoline and grease from boats, shore spillage, bilge discharge and distant sources in the watershed.
- Degraded water quality, i.e., high turbidity, low transparency and low oxygen content. Locally an abundance of coliform bacteria poses a health hazard.
- Growths of filamentous algae associated with high nutrient pollution loads.
- Sedimentation associated with storm runoff from the watershed and shoaling of the lagoon floor with formation of a black mud blanket.
- Disturbance of vital mangrove habitats by bulkheading, dumping and landfill to create dock space, berthing facilities and useable land.
- Loss of productive inshore clam and fishing grounds and reduction in vitality of bottom biota.

# LAGOON STRESS and IMPACT

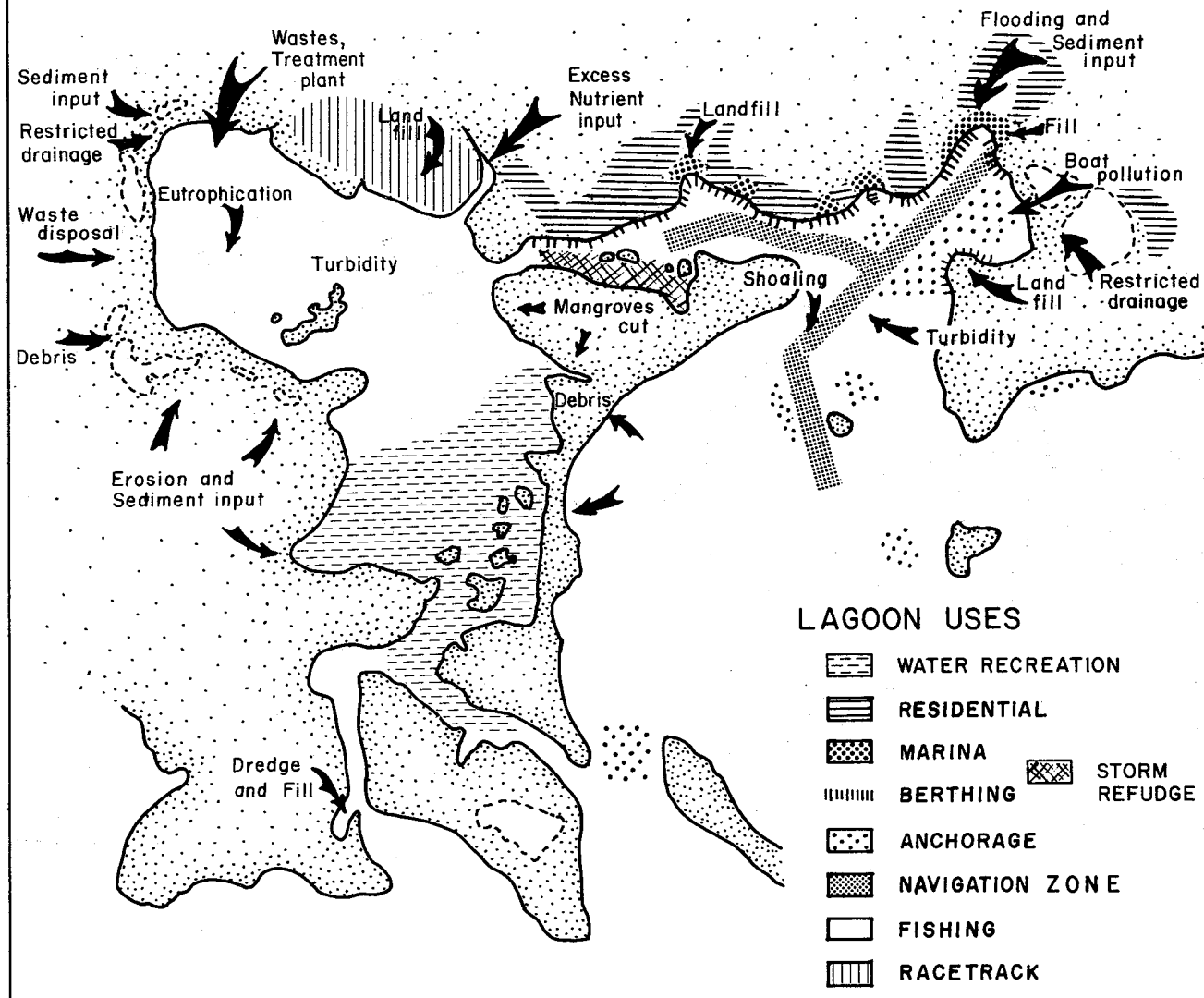


Figure 2. Schematic summary of stresses and impacts on the lagoon and bay in 1976-77.

- Restriction of drainage with loss of fishing capacity and stagnation of backwaters favorable to mosquito breeding.
- Shoals in the Benner Bay entrance channel which limit boat traffic and, in turn, marina use and economic viability.

Figure 2 summarizes schematically the distribution of selective stresses and impacts in relation to lagoon uses.

## 2. Study Objectives

The task now is to keep the lagoon healthy, to maintain the lagoon in its best achievable condition and to achieve a balance between the needs of the population and the health of the environment. We know a great deal about what people need and want but very little about the complexities of the environment and how it is affected by activities of man. If the lagoon is to be attractive and useful, it must be understood so that human activities can be anticipated and managed.

In recognition of the many problems, and the extent of local interest in the definition of viable options, the Island Resources Foundation launched a broad study of the lagoon in 1976 sponsored by the Virgin Islands Department of Conservation and Cultural Affairs. The study aims to (1) collect the basic scientific data needed to solve the immediate and impending problems of the lagoon environment; (2) to understand how the environment functions so that it can be managed and preserved while it is used; (3) to minimize impacts on the lagoon and (4) to find alternatives that balance the needs of a viable marina economy with preservation of a healthy mangrove ecosystem.

Specific questions addressed in this study are:

- What is the present condition of the water quality, sediment, and biota?
- What changes have taken place during the last decade due to impacts of sedimentation, landfill, development of the watershed and shores?
- How is the lagoonal area affected by flooding in the watershed?
- What areas are most susceptible to pollution?
- How can the entrance channel be improved to provide access for deeper draft boats without unacceptably altering functions in the lagoon and bay?
- What can be done to improve water quality and to alleviate deteriorating ecological conditions brought by pollution?
- What environmental values and guidelines should be used for planning long-term conservation and use of the area?

Although the lagoon has been previously studied by consultants and by scientists as a prospective site for a jet airport, clearly this information is not sufficient to solve present-day problems. New data are needed for different environmental conditions, especially the affects of high runoff from the watershed. They are also needed to evaluate the prospective impacts of proposed channel dredging and of a sewage treatment plant on slopes west of the lagoon with discharge into Stalley Bay. The specific objectives of the study are:

- To determine the present condition of the lagoon, its water, sediments and biota.
- To ascertain what conditions have changed over the last decade in response to human activities and to describe the magnitude of these changes.

- To analyze the processes causing the environment to change and to evaluate physical and biologic responses to these changes with the aim to improving water quality and restoring ecological conditions.
- To develop guidelines to minimize impacts on the lagoon and alleviate problems brought by development.

By analyzing changes in the environmental parameters and the responses to the changes, it should be possible to predict the direction and magnitude of future trends. The data obtained provide baseline information against which future changes can be assessed. Indirectly, they contribute to long-term monitoring of Virgin Island bays and they add to the regional inventory of island environments useful for long-range planning. To understand the lagoon environment not only requires observation of discrete units but observations of the interaction between units.

No ecosystem is static. It is continually changing in response to wind, tide, waves and solar radiation. There are daily, seasonal and long-term changes. With time, field observations were planned to embrace measurements in consecutive seasons, summer (1976), winter, spring and summer (1977). Most observations are concentrated in summer, July and August 1976. During this period diurnal and daily changes were recorded at contrasting energy levels: (1) a period of moderate energy with substantial easterly trade winds and moderate breakers on the reefs; (2) a period of low energy with light and variable winds and low breakers during which the tide varied from neap to spring range. These are but a few of the ever-changing environmental conditions obtained in the Lagoon.

### 3. Scope and Previous Studies

This study embraces the Mangrove Lagoon proper and Benner Bay, their entrance reaches, sediment floor and mangrove shores delineated in Figure 3. Since the lagoon is linked to the sea and to the watershed, contiguous drainage basins and waters of Jersey Bay are also considered. Although different features of the lagoon and bay are studied separately, it is recognized that the basic geographic element is the ecosystem. This embraces all the biologic and physical components in the lagoon that act together as an ecologic unit. No single part of the system operates independently.

The first survey of the lagoon shoreline and water depths was done in 1851 by Lt. G. B. Lawrance, a hydrographic surveyor of the British Admiralty. Offshore reaches were charted in 1924 by the U.S. Coast and Geodetic Survey and again in 1972-1973 by the National Ocean Survey, which included installation of a tide gauge in Benner Bay. A jet airport proposed in 1968 provided the impetus for investigating the ecology and hydrography of the lagoon; results are contained in consultant reports by Tabb and Michel (1968) and Michel (1970). At about the same time independent studies were completed by Department of the Interior biologists (McNulty, Robertson and Horton, 1968) and by scientists of the Caribbean Research Institute sponsored through the V. I. Department of Health (Grigg, vanEepoel and Brody, 1971). Additionally, Dammann (1969) collected data on productivity and distributions of salinity. Monitoring of water quality and pollution conditions continued to the present through efforts of

Grigg and vanEepoel (1972), Insular Environments (1975) and are summarized in Francois and Brown (1975). Data of these previous studies serve as a baseline for determining changes in water quality, bathymetry and certain ecological conditions. However, few previous data cover sediment characteristics relevant to dredging and benthic populations on a quantitative basis. Despite the wealth of aerial photographic coverage by different federal agencies since 1947, no effort seems to have been made to extract ecological information or to quantify and assess changes due to impacts of man.

#### 4. Methods and Procedures

Station locations. Stations were located to sample water pollution sources, the gradient of various water quality parameters and base line conditions in the lagoon and bay (Figure 3). Additionally, several "anchor" stations were sited in entrance reaches and at mouths of interconnecting passages for critical measurements of current speed and direction. One reference station was located in Jersey Bay where water is relatively free of pollution.

Bottom sediment samples and probes of sediment thickness were obtained at 50-meter intervals along bathymetric survey traverses shown in Figure 3. These stations cover a wide range of sediment types from different water depths and zones of varying sedimentation and pollution. Additionally, sediment samples were collected from reservoirs and alluvial soils in the watershed.

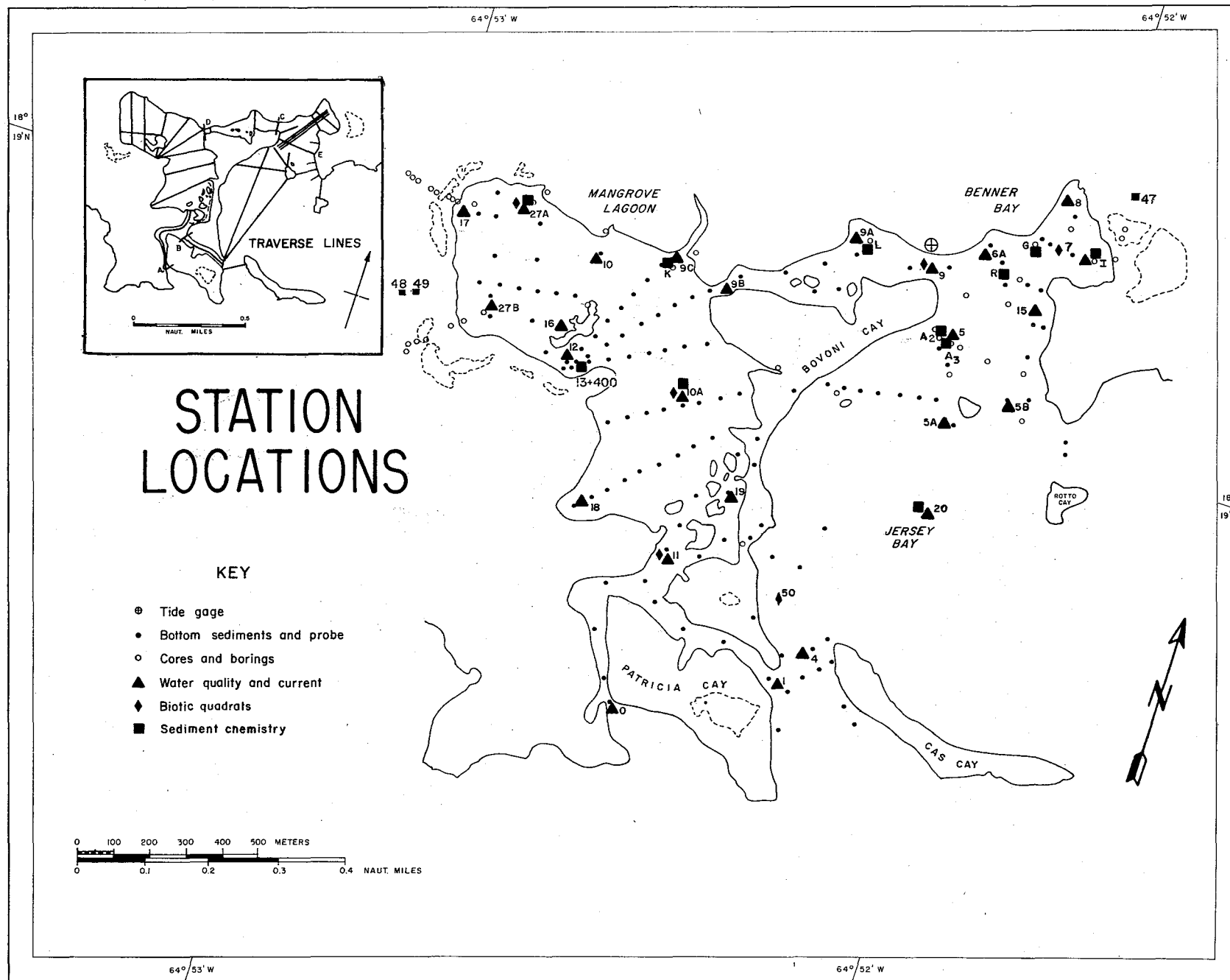


Figure 3. Location of sampling, measurement stations and location of bathymetric traverses, inset.

Borings were located along transects dictated by geologic conditions including thickness of unconsolidated sediment and horizontal variations in sediment lithology. They penetrated relatively thick sediment sections of the inner Lagoon and Benner Bay as well as selected shallow sections along the Bovoni Cay barrier island. Because of the difficulty in penetrating sand, most borings were made in soft peat or fine-grained sediment. The locations of borings and sampling stations is shown in Figure 3.

Instrumentation and Procedures. To define the bathymetry and in turn, the volume of water, cross sectional areas of flow and bottom geometry, soundings were made along traverses approximately 150 meters apart (Figure 3, inset). In shallow water less than about 1.3 meters deep, water depths were sounded at 10 meter intervals with a graduated pole, whereas in water deeper than 1.3 meters a Raytheon fathometer was employed. Positions of the traverses were established both by pelorus bearings and ranging. Ends of the traverses were positioned by inspection of shoreline detail on aerial photographs. Distances along the traverses and between stations were measured with a marked line.

The soundings were reduced to mean low water datum established from five months of continuous recording on a NOS gauge between November 1972 and March 1973 in Benner Bay. The soundings were then plotted on a base aerial photo enlargement scaled to about 1:7,500 and the contours were drawn.

A tide staff installed in Benner Bay provided reference data on tidal heights for bathymetric soundings, for mean high and

low waterline demarcation, for water quality measurements and for current observations. The staff was set to read zero at mean low water as established from tidal bench marks and five months of continuous gauge records. The staff and benchmarks are located on a pier and concrete sea wall in front of Frisby's brown house, Benner Bay.

The top 2cm of surface sediment was collected either by hand in a 5cm diameter core tube or with a "mini-grab". Character of the sediments was determined visually with the aid of a hand lens and grade scales. Samples were then frozen for future analyses of sediment chemistry, composition and particle size.

Thickness of loose sediment above firm base strata was determined by probing with a 6.1 meter (20 foot) steel rod. Depths of "refusal" to penetration by hand were recorded from station to station. Besides indicating the maximum depth of resistance, the probe recorded the thickness of the surface mud blanket and interlayers between the surface and the base.

Borings were made with a Davis Peat Sampler which takes 30 cm long sections in a 3.8cm diameter core barrel. By adding extensions to the core head, relatively undisturbed cores were obtained down to a depth of 6.5 meters.

Short cores were obtained manually by driving a 7.6cm (3-inch) diameter PVC pipe into the bottom to depths of approximately 50 to 80 centimeters. Part of the cores were cut lengthwise, photographed and sampled at 10 to 30cm intervals. Other cores were retained in the pipe and frozen for chemical analyses and radiometric dating.

Water quality parameters were mainly measured in situ with instruments provided by the Virgin Islands Department of Conservation and Cultural Affairs.

Water temperature and dissolved oxygen concentrations were measured with an in situ probe of a YSI (Yellow Springs Instrument) oxygen meter, model 54A, equipped with a membrane covered polarographic probe. The measurements were calibrated at each station by running a saturated water sample having the same temperature as the sample water. The ratio of these readings and the corresponding theoretical saturation value provided the oxygen concentration in mg per liter.

During the January 1977 survey, salinity, pH and temperature were measured with an in situ Marteck unit. The conductivity probe was initially calibrated in the laboratory against standard sea water and the pH probe was buffered with a pH 7 solution. During the August 1976 survey, salinity was analyzed on water samples returned to the laboratory with an Endeco refractometer. The unit was standardized against distilled water and standard water having a salinity of 34.5 ppt.

Turbidity of water samples returned to the laboratory was determined within 24 hours of collection with a Hack turbidometer, model 2100A standardized with Formazin suspensions. Suspended solids of fresh samples were analyzed gravimetrically using Millipore filters of 0.80 pore size. Transparency of the water was measured with a white-black Secchi disk, 30cm in diameter. Because the disk could not be used at night and often rested on the bottom, the number of disk readings is limited.

For surveys other than January 1977, the pH of water samples was run in the field using a Beckman pH meter, model 1009, buffered with a pH 7 solution.

Rates of gross production of organisms in suspension were determined by conventional light-dark bottles installed in situ. BOD bottles were set for 24 hours, both near the surface and near the bottom of each anchor station. Similarly, rates of gross production and respiration of the waters en toto were determined from diurnal oxygen curves using the graphical method of Odum and Hoskins (1958).

Dissolved reactive phosphorous concentrations were measured on all survey samples in the DCCA laboratory, using the ammonium molybdate and stannous chloride reduction method developed by Robinson and Thompson (1948).

Current speed and direction were mainly measured with a small drogue, 4-meter line and a stop watch. A steel rod was set into the bottom away from the influence of flow on the boat, and the time of excursion was measured over a 4-meter distance. At the end of the excursion the direction was observed with a pelorus type hand bearing compass. When currents were weak and variable and the drogues affected by surface winds, dye patches were released to observe the current direction. Where current speed reached more than 0.1m/sec, drogue and dye observations were supplemented with a Marsh-McBirney electromagnetic current meter, model 511.

Laboratory methods for toxic trace metals and organic pollutants in sediments are given in a separate section covering

pollutants in bottom sediments.

Meteorological conditions affecting water quality and circulation were observed concurrently with water measurements. Air temperature was measured in the shade with a stem thermometer; wind speed was measured with a hand-held Sims anemometer while wind direction and wave direction were observed with a hand-held compass; and wave height was estimated visually.

Observational Period and Data Acquired. Field observations were concentrated during a four-week period in August 1976. Additionally, quarterly surveys of the water quality and biota were made in January 1977, March-April 1977 and July-August 1977. Altogether, the field effort resulted in more than 20 "dip" stations occupied quarterly for measurements of water quality and current, 12 stations occupied in August 1977 for diurnal measurements of water quality and current, 28 borings, 20 shallow cores, 9,200 meters of sounding tracks, 5 benthic quadrat stations occupied quarterly for samples of biota, aerial reconnaissance and surface observations covering an area over 944,000 square meters. These observations provided a larger volume of data and greater spatial detail than afforded by previous studies.

Meteorological conditions, waves, wind and precipitation, affecting water quality and circulation during the observational periods varied from very mild to moderate. Precipitation and freshwater runoff were limited to local showers and sporadic discharges.

## Mangrove Studies

The historical distribution of mangroves in the area was studied from the shoreline and manglar configurations recorded on the 1851 Admiralty survey chart. Additionally, aerial photographs of 1947, 1954 1965, and 1971 were examined and former biological surveys were reviewed, i.e., McNulty et. al. (1968), Grigg et. al. (1971), and Olsen and Dammann, (1973).

The mangrove areas examined in the Mangrove Lagoon and Benner Bay are: (1) Patricia Cay, (2) Bovoni Cay, (3) West shore of inner lagoon (station 17 vicinity), (4) Compass Point salt pond.

Since salinity is a key factor affecting the distribution of mangroves (Cintron and Lugo, in press), surface waters bathing the mangroves as well as the interstitial soil salinity were sampled. Salinity was measured with a hand held refractometer calibrated against a Bessett Berman bench salinometer. Samples were also collected for atomic absorption analysis of major elements (Na, K, Ca Mg) and some minor elements.

Elevation of the soil surface was measured by conventional leveling with a survey transit. The elevations were related to the local tidal datum.

Structural characteristics of the mangrove stands such as basal area, D.B.H. (diameter of breast height), height of vegetation and leaf length-width ratios were also measured at various locations. Leaf color was determined by a Munsell color chart for plant tissues.

Benthic Biota. To account for the species present, their seasonal variation, abundance and standing crops, benthic organisms were sampled and observed in three ways: (1) diver transects, (2) quantitative quadrat sampling, and (3) cores and grabs.

Diver transects were made in clear water areas to delineate the limits or boundary of various benthic communities, to enumerate species and to determine the presence of transitory species. The NOS 1972 aerial photographs provided a base chart to record predominant cover and any evidence of community boundary shifts since the photos were taken. In areas of high turbidity, diver transects were supplemented by repeated dredge hauls.

Quantitative sampling consisted of repetitive sampling at five basic stations with  $0.25 \text{ M}^2$  quadrats. The boat was positioned with cross fixes using a magnetic compass, the quadrat placed on the bottom and all the living material and surrounding sediments were dug out to a depth of about 10 cm. The material was placed in a mesh bag ( $0.5 \text{ mm}^2$  mesh size) and the fine sediments washed out. The remaining biological material was preserved in 5 percent buffered formalin with rose bengal (a biological stain) and returned to the laboratory for sorting, counting or weighing. All plant species were also dried at  $100^\circ\text{C}$  and dry weights recorded. The stations were repetitively sampled in August 1976, January, April and August 1977. Locations established by visual ranges in the field, are shown in Figure 3.

Grab samples were obtained with a 0.1 M<sup>2</sup> Peterson grab while cores were taken with a 170 cm<sup>2</sup> box core driven into the bottom to a depth of 15cm. During the August 1976 survey, five replicate cores and grabs were taken at each station. Plants taken in the core were separated and the sediment was seived wet through nylon bags with a maximum mesh opening of 1.0 mm x 0.6 mm.

All live animals other than foraminifera were picked from the sieved sediments (and the separated plants) either alive or after the sample was preserved with buffered 5 percent formalin and Rose Bengal. Examination of the sediment was by both naked eye and dissecting microscope at 6 or 12X. Dead organisms represented by shells, etc. were excluded from analysis because of possible transport.

Simultaneously the biological origin of coarse carbonate sediments retained by the sieve was recorded. Extracted organisms were preliminarily identified, counted, fixed, and stored in alcohol for specific identification.



## 5. Description of the Lagoon System.

The Mangrove Lagoon with its contiguous passages, bays and backwaters form a triangular estuarine system 2 km (1.2 miles) long and about 1.3 km (0.6 miles) wide overall. Because the shores are very irregular the average width is less than 0.5 km. The system lies in a northeast-southeast trending fault zone of sedimentary fill at the mouth of Turpentine Run, the largest stream on St. Thomas. The mangrove-fringed islands and shallow waters form an embayment in the coast which contrasts with the pattern of steep, rocky headlands and narrow sand or cobble beaches along the rest of the south coast of St. Thomas.

Bovoni Cay, the largest island in the system, is a curved barrier island. Together with Cas Cay, Patricia Cay, Bovoni Cay separates the lagoon from Jersey Bay and the sea (Figure 4). These features effectively dampen wind and wave energy reaching the lagoon. They create the quiet water necessary for extensive mangrove growth and development of a safe harbor for small boats.

The smooth arcuate seaward shore of Bovoni Cay is locally interrupted by clumps of mangroves that have advanced into the adjacent shallows of Jersey Bay (Figure 4, mi). By contrast, the inner lagoon margin is indented with coves that reflect the history of gradual submergence in the area. Along the shore of Benner Bay and Bovoni Passage, the mangrove fringe has been largely replaced by marinas, docks and shore development (Figure 5). Table 1 summarizes geographic and hydrographic dimensions of the Mangrove Lagoon and Benner Bay.

Figure 4. Bovoni Cay, center, a mangrove fringed barrier island that protects the Mangrove Lagoon and Bovoni Passage (BP) from storm waves. Piecemeal development of waterfront, lower right, creates degraded water quality and loss of natural shore area. Recent mangrove growth stabilizes shoals (Mi). Aerial view southwest toward Long Point (LP), August, 1977.

Figure 5. Entrance reaches to Benner Bay (BB) between Bovoni Cay (BC) and Compass Point (CP). Shore development along Benner Bay and Bovoni Passage has replaced the natural mangrove fringe. Residential development above the bay and in the drainage basin at Tutu (t) threaten to alter the pattern and quality of runoff into the bay.

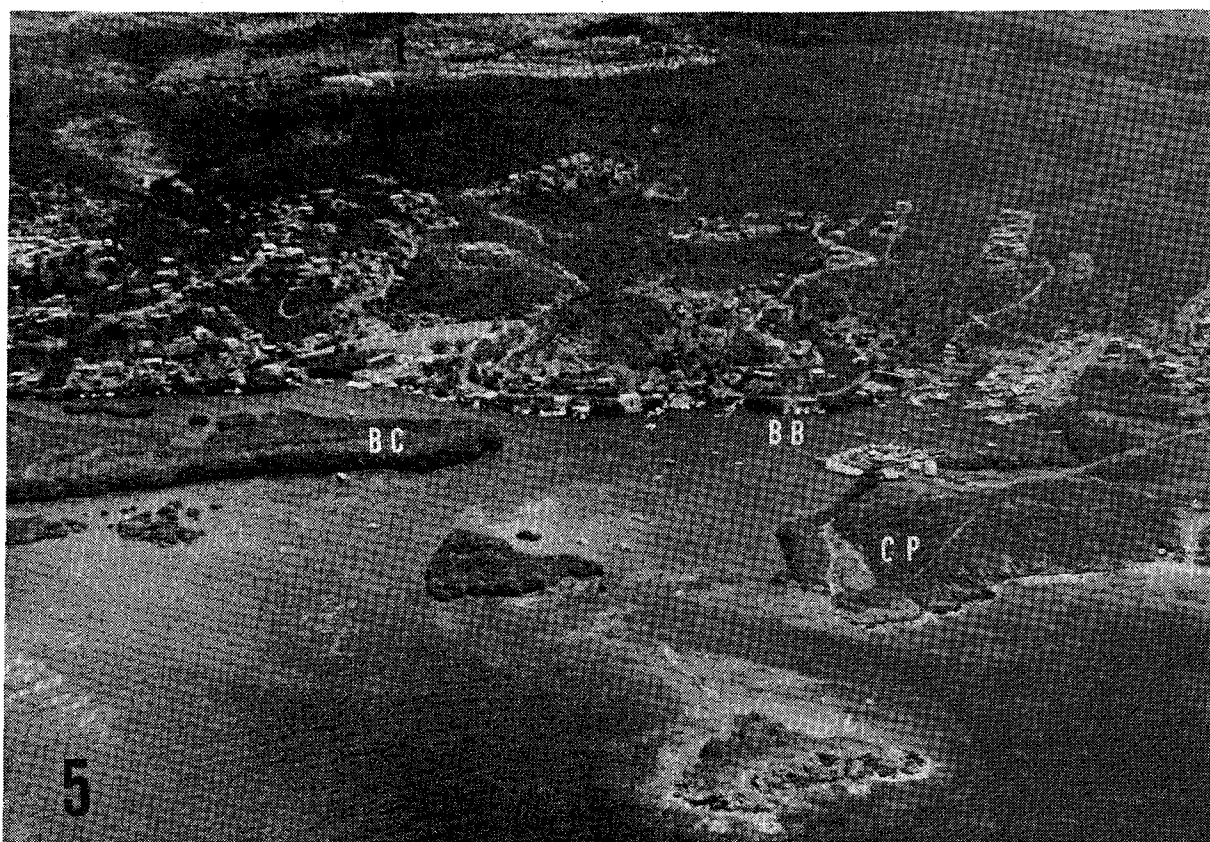


Table 1. Summary of geographic and hydrographic dimensions for the Mangrove Lagoon and Benner Bay.

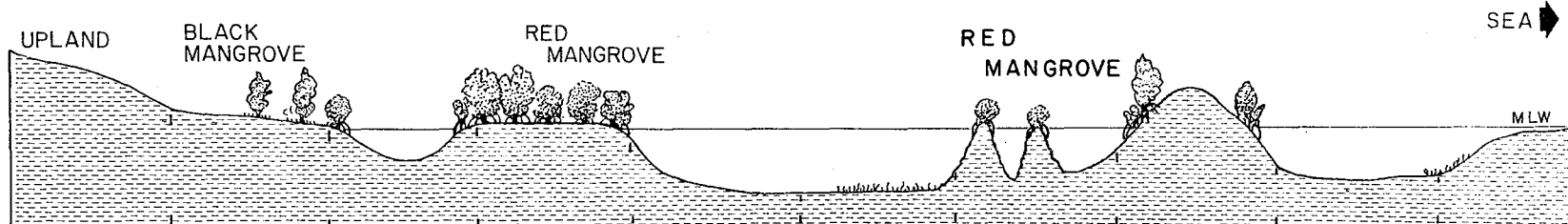
| <u>Parameter</u>              | <u>Mangrove Lagoon<br/>(including passages)</u> | <u>Benner Bay</u>      |
|-------------------------------|-------------------------------------------------|------------------------|
| Length                        | 1.6 km                                          | 0.4 km                 |
| Width                         | 0.35 - 1.0 km                                   | 0.15 - 0.30 km         |
| Mean Low Water Area           | 614,339 m <sup>2</sup>                          | 128,891 m <sup>2</sup> |
| Mean High Water Area          | 809,471 m <sup>2</sup>                          | 135,607 m <sup>2</sup> |
| Volume Below MLW              | 805,675 m <sup>3</sup>                          | 160,394 m <sup>3</sup> |
| Mean Depth Overall            | 1.3 m                                           | 1.3 m                  |
| Maximum Depth                 | 3.2 m                                           | 2.2 m                  |
| Mean Tide Range               | 0.27 m                                          | 0.27 m                 |
| Tidal Prism                   | 191,238 m <sup>3</sup>                          | 35,713 m <sup>3</sup>  |
| Shoreline Length<br>Along MLW | 1,374,641 m                                     | 13,201 m               |
| Drainage Basin<br>Total Area  | 12.7 km <sup>2</sup>                            | 0.8 km <sup>2</sup>    |

It is important to note that the lagoon is a dynamic system on a geologic as well as an ecological time scale. The historical pattern of mangrove vegetation has changed in the last 30 years. And the lagoon floor has changed considerably in response to natural processes. These changes still go on today, but they are now mainly influenced by man.

As an ecosystem the Mangrove Lagoon area consists of ten distinctive subsystems or ecological zones. Most of these units are linked by the flow of water. Table 2 summarizes attributes of these zones and their relative position with respect to each other, to water depth and to distance seaward.

Table 2. Ecological zones of the Mangrove Lagoon.

## ECOLOGICAL ZONES



| ATTRIBUTES                                  | DRAINAGE BASIN                                 | HIGH TIDAL FLATS "SALTURNS"           | PONDS & INNER LAGOONS     | MANGROVE FOREST & SWAMP                                | OPEN WATER, LAGOON & BENNER BAY            | GRASS BEDS (LAGOON) THALASSIA                              | MANGLAR CAYS                                            | BARRIER ISLAND              | PASSAGES, ENTRANCE CHANNELS  | BACK REEF FLATS                            |
|---------------------------------------------|------------------------------------------------|---------------------------------------|---------------------------|--------------------------------------------------------|--------------------------------------------|------------------------------------------------------------|---------------------------------------------------------|-----------------------------|------------------------------|--------------------------------------------|
| AREA IN ACRES                               | 3,334                                          | 10.7                                  | 14.34                     | 49.9                                                   | 183.0                                      | 11.0                                                       | 4.5                                                     | 15.3                        | 14.8                         | 10.4                                       |
| WATER DEPTH OR ELEVATION: m                 | Range 0 to 260                                 | Range 0.2 to 0.4                      | Range 0.1 to 0.3          | Range 0 to 0.3                                         | Mean 1.3                                   | Mean 0.8                                                   | Range 0 to 0.3                                          | Range 0.3 to 2.6            | Range 0.2 to 3.2             | Range 0.1 to 0.3                           |
| DRAINAGE OR FLUSHING                        | Intermittent                                   | Partly Covered on Spring & Storm Tide | Slow                      | Red Mangrove. Covered with water most of year          | Slow to Moderate                           | Slow to Moderate                                           | Covered by Normal Tides                                 | Rapid Drainage              | Moderate                     | Rapid                                      |
| SUBSTRATE OR BED SEDIMENT                   | Gravelly Clay Loam                             | Clay & Silt                           | Organic Muck              | Peat                                                   | Mud, Sandy Mud, Muddy Sand                 | Muddy Sand Sandy Mud                                       | Peat, Sandy Mud                                         | Sand                        | Sand                         | Rubble, Sand                               |
| DISTINCTIVE ECOLOGICAL CHARACTER & FUNCTION | Dry Forest with Sactus, Secondary Snrub growth | Barren or Algal Covered               | Bird and Wildlife Habitat | Forest Cover, Nutrient Production, Shore Stabilization | Plankton Habitat, Feeding and Nursery Area | Confinement, Nursery Habitat, Production, Nutrient Storage | Nutrient Production, Shore Stabilization, Sediment Trap | Storm Barrier, Sand Storage | Water Exchange, Feeding Area | Storm Barrier, Sediment Trap, Feeding Area |

Aerial Photo Evaluation. From an eye-in-the-sky of a vertical aerial camera having a 15 cm (6 inch) focal length, one can see at a glance many features of the lagoon environment. Such features are often not represented on maps or charts which are often out-dated by rapid changes that have taken place in the area. Also, many features are so large they cannot be readily seen or measured on the ground or from a boat. When aerial photographs taken from time to time are compared, they reveal changes in environmental features such as shifts in the distribution of terrestrial plant communities, benthic biota, and shoreline changes.

Aerial photographic coverage examined in this study is listed in Table 3.

Table 3. Aerial photographic coverage of the Mangrove Lagoon and Benner Bay.

| <u>Source</u>           | <u>Date</u> | <u>Scale</u> | <u>Type</u> |
|-------------------------|-------------|--------------|-------------|
| National Ocean Survey   | Feb. 1974   | 1:12,000     | Color       |
| National Ocean Survey   | Dec. 1972   | 1:12,000     | Color       |
| National Ocean Survey   | Nov. 1972   | 1:12,000     | Color       |
| National Ocean Survey   | Nov. 1971   | 1:20,000     | Color       |
| National Ocean Survey   | Mar. 1965   | 1:15,000     | B&W         |
| National Ocean Survey   | Feb. 1964   | 1:24,000     | B&W         |
| National Ocean Survey   | Nov. 1958   | 1:10,000     | Color       |
| U. S. Geological Survey | Jan. 1954   | 1:23,600     | B&W         |
| U. S. Navy              | Mar. 1947   | 1:30,000     | B&W         |

A black and white reproduction of a color photograph (Nos. 72E-7400) taken at 1.8 km (6,000 foot) altitude dated Nov. 23, 1972, the most recent coverage of the entire study area, is shown in Figure 6. Most conspicuous is the contrast in tone between the light-toned areas representing cultural features and the dark-toned areas representing natural features, mainly vegetation submerged in the water or on land. Important natural features are: Compass Point (CP) a rocky headland that protects Benner Bay together with Manglar Island (MI) and Rotto Cay, Bovoni Cay (BC), covered with dense stands of mangrove and scrub that shelters most of the lagoon while Patricia Cay (PC) and adjacent coral reefs (CR) protect it from the south. Dense stands of red mangrove (RM) border the inner lagoon margin while sparse stands of partly dying black mangrove (BM) fringe innermost reaches. Farther landward the smooth clayey surface of dry high flats or "salterns" with salt efflorescence is marked by a very light, nearly white, tone (west of letters BM). The inner lagoon floor (IL) is nearly uniform grey tone representing turbid water and a mud bottom while the middle lagoon floor (ML) is mottled with dark vegetated patches of Thalassia covering light-toned Halimeda sand. In passages farther seaward, extreme light tones represent reflectance of Halimeda and coral sand (s). Sand (sd) is also evident in light-toned zones along the shallow nearshore zone off Bovoni Cay which is affected by wave action and growths of Halimeda-Penicillus, calcareous green algae. Crenulated light-toned patches farther seaward are blow-out zones (b), i.e., sand patches exposed by erosion of the turtle grass cover (t).

the first of these is the fact that the  
the second is the fact that the

the third is the fact that the

the fourth is the fact that the

the fifth is the fact that the

the sixth is the fact that the

the seventh is the fact that the

the eighth is the fact that the

the ninth is the fact that the

the tenth is the fact that the

the eleventh is the fact that the

the twelfth is the fact that the

the thirteenth is the fact that the

the fourteenth is the fact that the

the fifteenth is the fact that the



The most striking human alteration of the area is the racetrack (RT) development at the mouth of Turpentine Run (TR). This consists of both landfill and canals dug in an alluvial delta. Drainage from Turpentine Run is diverted through a ditch and backwater near TR. Farther landward runoff is channelized by concrete training walls. Extensive housing occupies alluvial slopes just north of the lagoon; additional buildings and marina complexes are obvious along the shoreline of Bovoni Passage and Benner Bay (BB). A more subtle feature is the plankton or sediment-rich plume extending seaward through the main boat channel entrance (p). More obvious are the plumes flowing from the treatment plant (x), which is the site of treated sewage discharge.

The environmental and cultural changes that have taken place in the area during a 25 year period are indicated by comparing the 1972 photo (Figure 6) with another dated 1947 (Figure 7). The most striking feature of the 1947 photo is the lack of vegetation on alluvial slopes, adjacent to the lagoon as well as on the barrier island, Bovoni Cay. This condition was caused by extensive cutting of scrub trees and mangroves for fuel and charcoal (Pedrito Francois, personal communication). Cultural features like housing and wharfs are absent except near road junctions at Benner (B) and Nadir (N). The shore of Benner Bay is more extensively fringed with mangroves in 1947 than in 1972. However, mangrove stands (M) are very narrow along the inner lagoon margin; they are backed by denuded flats with scattered trees representing a cut-over area. Turpentine Run (TR)

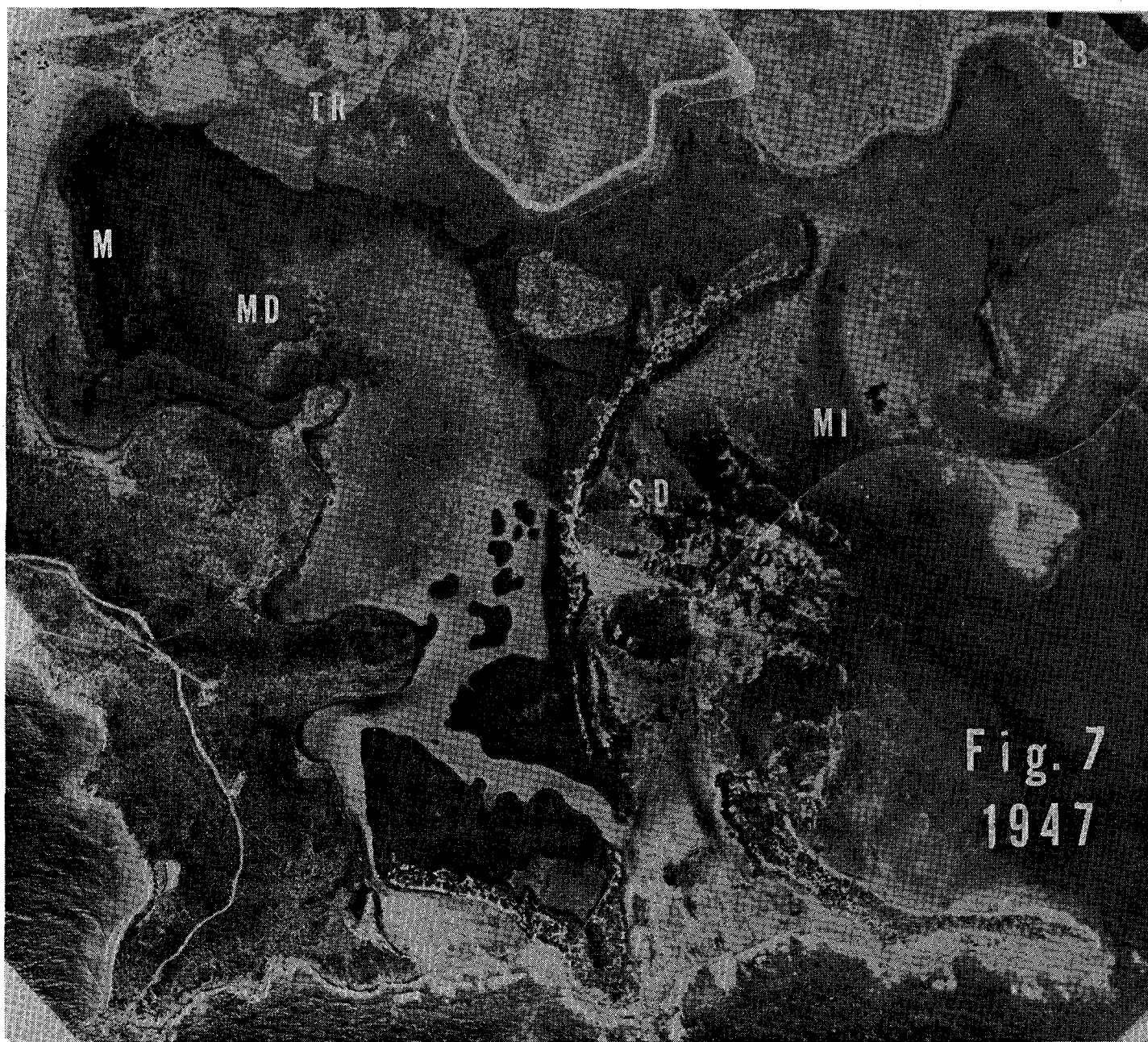


Figure 7. Aerial photograph of the Mangrove Lagoon and Benner Bay taken by the U. S. Navy, March 3, 1947.

drains into the lagoon head rather than into middle reaches east of the racetrack. Most of the lagoon proper is covered with turtle grass beds, Thalassia. These are dense (dark-toned) in inner reaches and sparse or interspersed with Halimeda sand in middle reaches. Also, sand (sd) is more extensively exposed on the nearshore bottom of Jersey Bay in 1947 than in 1972. Likewise, turtle grass beds are more limited in 1947 (Figure 7). Manglar Island (MI) and Middle Island (MD) are greatly enlarged in the 1972 photo, indicating extensive growth of mangrove cays in middle reaches of the lagoon did not change appreciably between the two photos, and they are essentially the same on the 1851 hydrographic chart. The entrance shoals of Benner Bay are more extensively covered with sea grass and stabilized in 1972 than in 1947 when sand, probably Halimeda, was exposed over a large area. However, grass beds which are clearly visible on the floor of Benner Bay and inner lagoon reaches in the 1947 photo are replaced by dark-toned mud and turbid water in the 1972 photo.

Bathymetry. Water depth and bottom geometry are basic data for measuring flushing and sedimentation rates, for siting boat channels, and for determining dredge quantities.

The lagoon floor is a shallow pan-like basin less than 2.1 meters deep. It is partly divided by Middle Island and by a shoal between Middle Island and Bovoni Cay. The contours of Figure 8 reveal a relatively deep basin 1.5 - 2.1 meters deep in southern central reaches. Sides of the lagoon are relatively

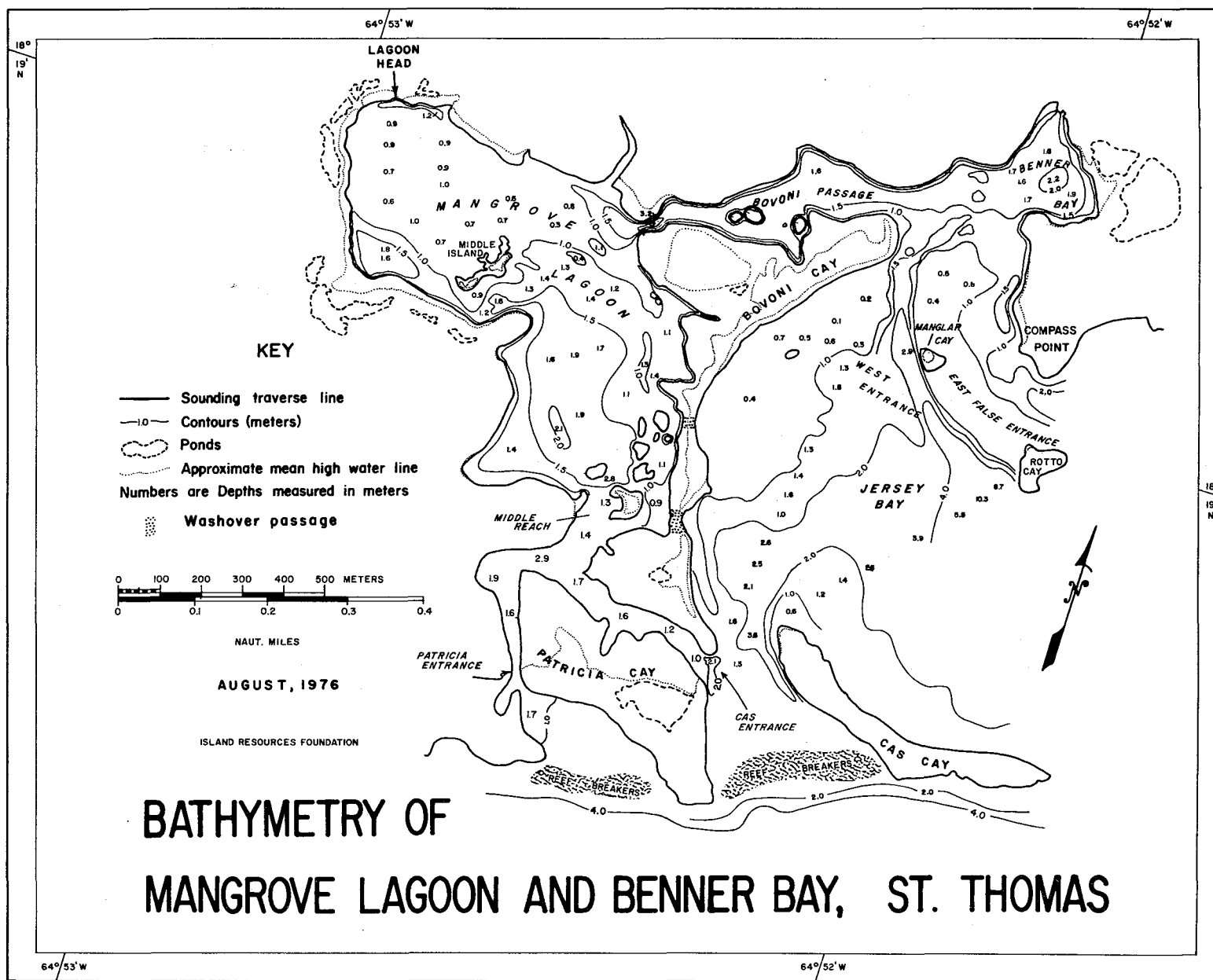


Figure 8. Bathymetry and shoreline of the Mangrove Lagoon and Benner Bay. Shoreline is close to the mean low water line.

steep, especially along passages and around islands of Middle Reach which are locally undercut to 2.8 meters on their seaward side. Steep sided channels with substantial water depths and scattered tiny islands west of the middle part of Bovoni Cay mark former inlet channels and routes of storm flow from Jersey Bay through the cay. A counterpart of those channels seaward of Bovoni Cay is indicated by a deep zone extending shoreward near a large washover area (Figure 8). These are the last vestiges of many channels through the cay that were filled with sediment prior to 1851. The low elevation of the cay in these zones today, less than 1.5 feet above MLW, allows water to wash across the cay during short periods of high spring tide and storm tide.

Passages connecting the lagoon are often deeper than the lagoon itself. The greatest depth, 3.2 meters, occurs in the narrowest part of Bovoni Passage where it joins the lagoon. Under normal conditions, currents flowing through this reach are faster than elsewhere, up to 15 cm/sec. Mangrove-fringed sides are steep and often undercut. These passages are an important element of the lagoon system because they control the exchange of water between the lagoon and the sea. Such links determine the range of salinity and the rates of tidal mixing. They are the chief avenues for discharge of wastes and storm waters. Without free exchange through the passages, the lagoon would become a stagnant pond.

Benner Bay is a deeply indented spoon-shaped harbor, 0.5 km (0.3 miles) long and 0.25 km (0.15 miles) wide (Figure 9). Its maximum depth is 2.2 meters (7.0 feet) near the center. The

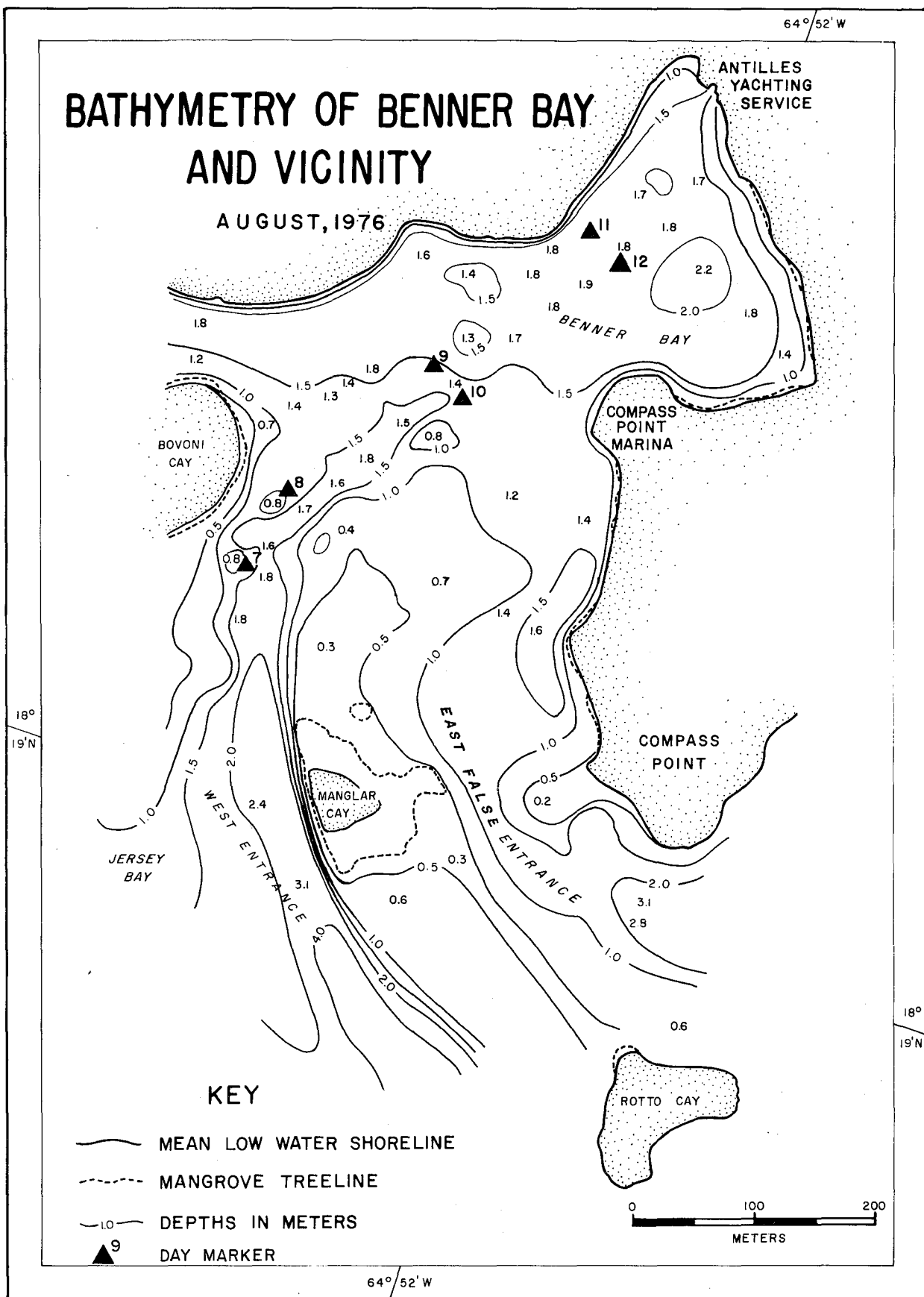


Figure 9. Bathymetry and shoreline of Benner Bay.

# BOTTOM PROFILES

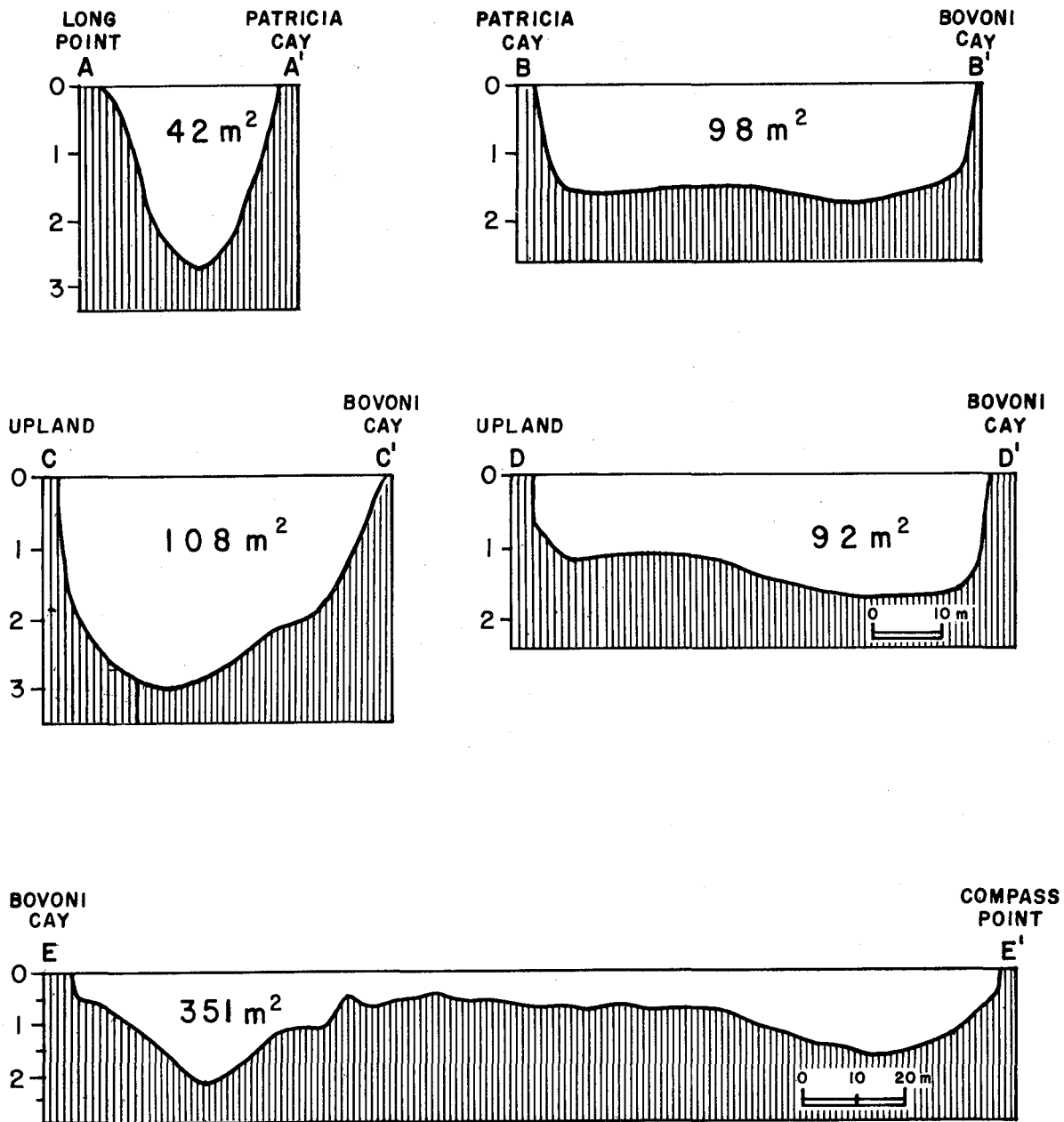


Figure 10. Selected bathymetric profiles and cross sectional areas of flow. For locations see Figure 3, inset.

contours of Figure 9 show a shallow sill, mainly less than 1.5 meters (4.8 feet), across the inner entrance. This separates deep parts of the inner bay from channels and passages of the outer entrance reach. The outer entrance reach consists of two channels separated by an elongate shoal between Rotto Cay and Manglar Cay. The East False Entrance channel is shallow, less than 1.3 meters (4.2 feet) deep, and irregularly curved with a transverse shoal that restricts the channel between Compass Point and Manglar Cay. The West Entrance channel, which is the main boating channel, is narrowly funnel-shaped and broadly curved (Figure 9). The inner portion of this channel is largely limited to depths less than 1.5 meters (4.8 feet) for a width of 16 meters (51 feet), whereas outer parts along Manglar Cay and farther seaward are greater than 2.2 meters deep (7.0 feet) for a width of 35 meters (110 feet). At pile "7" the channel changes course by 120°. In this bend two small shoals extend channelward and form a navigation hazard (Figure 9).

Figure 10 shows representative bathymetric profiles of the 28 sections surveyed in the lagoon area. Channel floors are mainly molded of loose sediment, shell, coral debris, and sand or mud; rock and partly consolidated sediment is absent. Most of the profiles are broadly U-shaped or nearly rectangular with flat floors and steep sides.

Bathymetry Changes. Comparison of water depths on old charts with those obtained in the present survey shows no large changes in the bottom geometry or shoreline configuration despite local

assertions to the contrary. Two depth soundings displayed on a British Admiralty chart dated 1851 (Figure 11) are about 0.39 meters (1.3 feet) deeper near the lagoon head and in southern reaches. This is in accord with an estimated sea level rise of 0.45 meters (1.5 feet) during the last 125 years. It implies low sedimentation in the inner lagoon near the lagoon head.

By contrast, water depths in the eastern part of the lagoon off the entrance of Turpentine Run are 0.10 to 0.40 meters (0.3 to 1.3 feet) shoaler in 1977 than in 1851 (Figure 12). Shoal water depths occur in this zone despite a probable 0.45 meter (1.5 foot) rise in sea level during the last 125 years. Therefore, the "excess" shoaling or rate of sedimentation in eastern reaches is about 0.7 meters (2.4 feet) per 100 years. Composition of sediments in the shoals (Figure 30) indicates most of the material is supplied by growth of Halimeda which contributes sandy components while about 30 to 60 percent of the material is mud most likely supplied from Turpentine Run. Distribution of the "mud blanket" is delineated in Figures 30 and 38 (Halophila and large Sabellid zones). Because most former surveys are not based on a common tidal datum, depth differences reveal only depth changes greater than about  $\pm 0.15$  meter (1 foot).

The central floor of Benner Bay is about 0.45 meters (1.5 feet) deeper as a result of sea level rise over the last 125 years. By contrast, the extreme inner part, near Antilles Yachting Services, is shoaler by about 0.20 meters (0.7 feet) as a result of sediment infilling from the land.

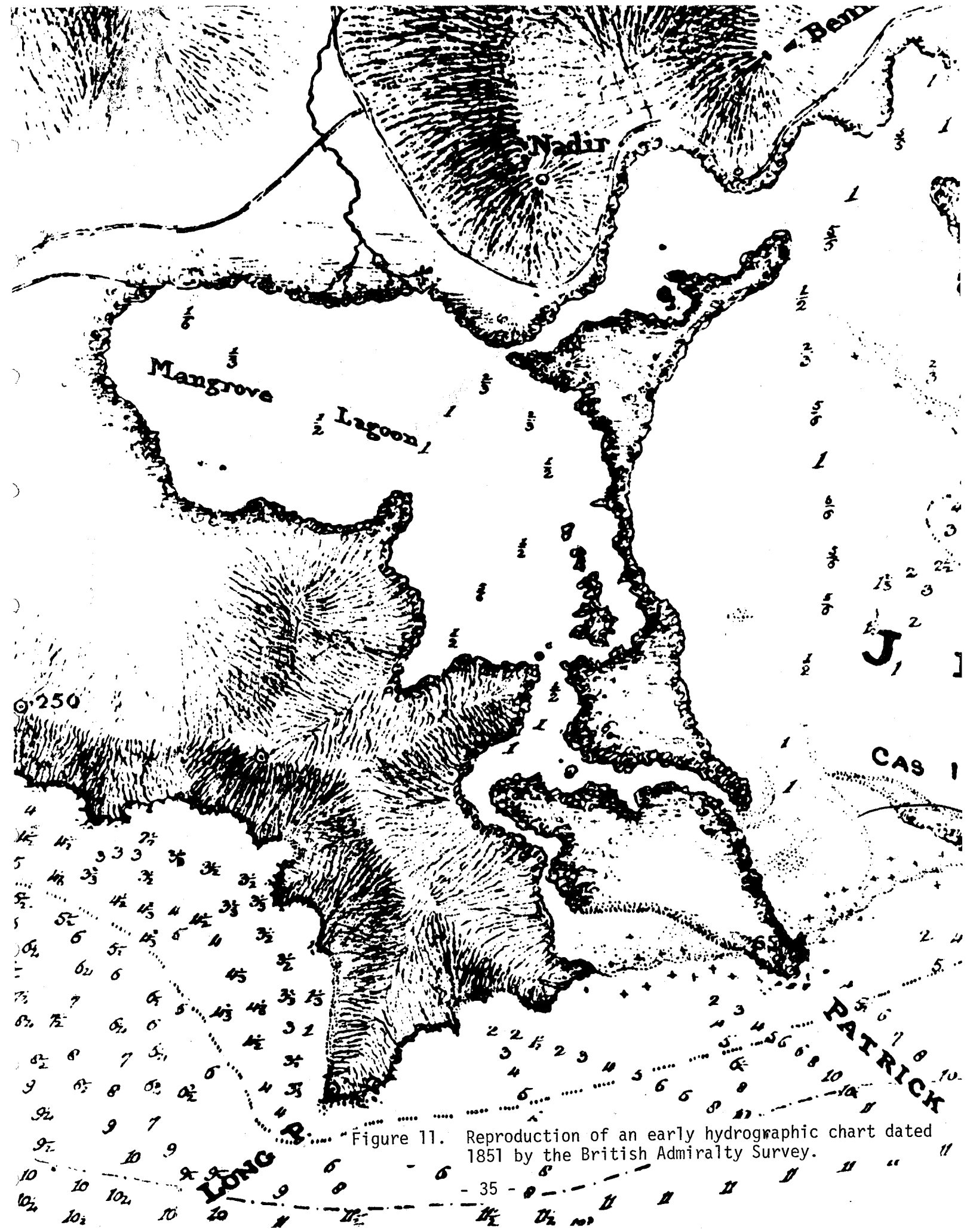


Figure 11. Reproduction of an early hydrographic chart dated 1851 by the British Admiralty Survey.

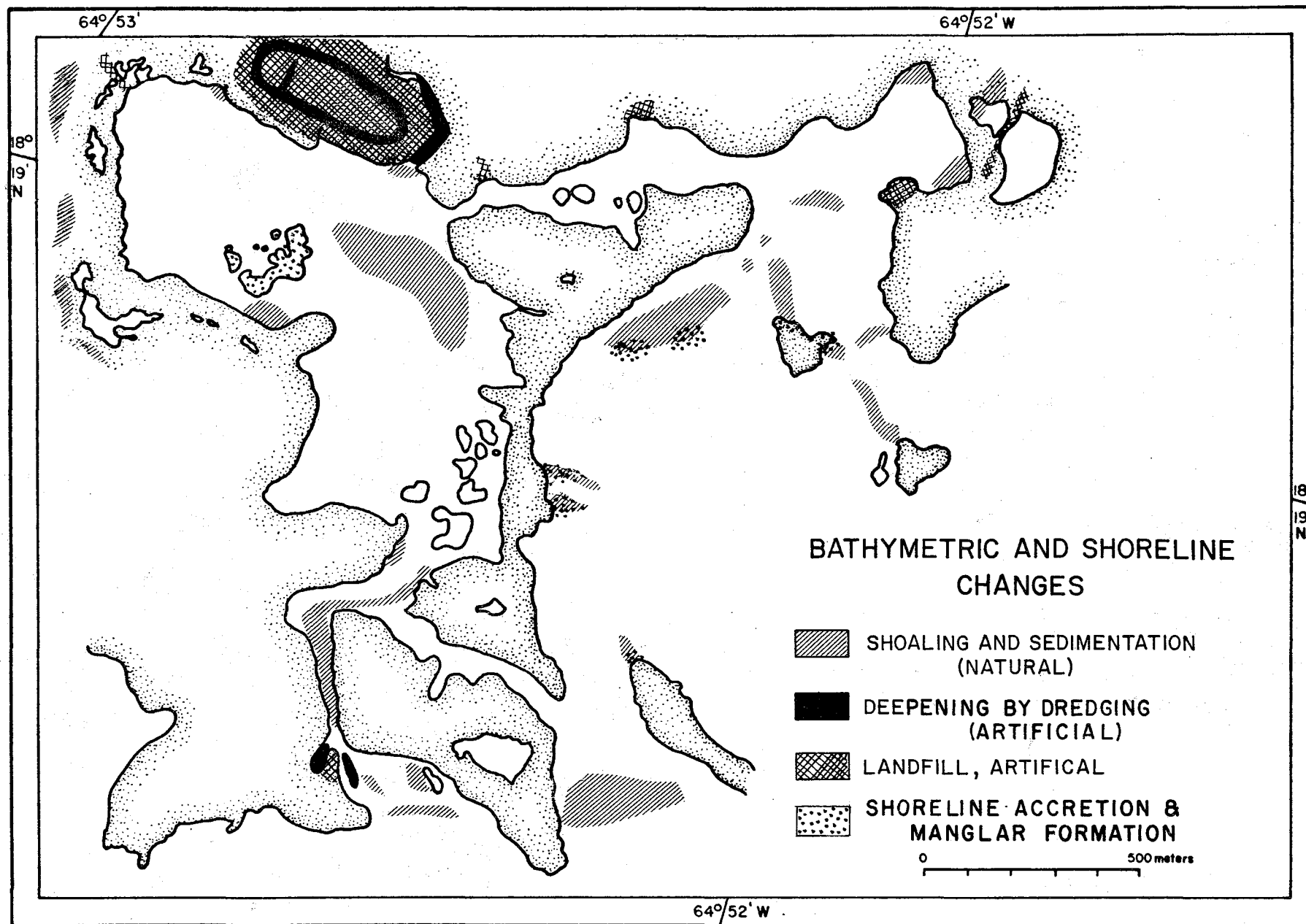


Figure 12. Bathymetric and shoreline changes showing zones of shoaling, deepening and landfill. Shoaling zones are delineated from water depth differences as well as from sediment cores and aerial photo analysis.

Comparison of water depths along the Benner Bay navigation channel sounded by Dr. J. Zeigler for Antilles Yachting Services in 1970 show very small changes over the 6-year period. Inner reaches of the bay are generally shoaler by about 20 cm (0.7 feet). The floor of the entrance channel between piles "8" and "9" is generally deeper in 1976 than in the 1970 survey by about 15 cm (0.5 feet), whereas sides of the channel are shoaler by 20-60 cm (0.6 - 1.9 feet). This trend is most likely caused by propeller wash of boat traffic which acts to deepen central parts and shoal the sides. Consequently, the channel is narrowed along the 1.1 meter (3.5 foot) depth curve. Berths along Bovoni Passage are reportedly "dug out" and maintained by propeller wash.

6. Watershed and Drainage. The lagoon system acquires some of its water and much of its sediment from the upland watershed or drainage basin. Because the lagoon is linked to the watershed, changes in topographic and flow characteristics of the watershed affect many functions in the lagoon itself. Fresh water inflow governs the salinity of lagoon water which, in turn, affects the types of organisms, their distribution and abundance. Additionally, the amount of sediment, nutrients, organic debris and some pollutants carried into the lagoon is determined by stream runoff. These materials affect lagoon water quality, sedimentation rates and plant production.

The drainage basin receives about 40 inches of rainfall annually. As much as 8 inches has been recorded from a single storm. However, annually runoff amounts to only 2 to 8 percent

of the rainfall.

The drainage system of the Mangrove Lagoon and Benner Bay consists of four sub-basins (Figure 13). Most stream channels are dry and carry only intermittent storm runoff. The lagoon receives drainage conveyed through small guts or washes, through local culverts, and through a major stream channel, Turpentine Run.

Turpentine Run which drains into the Mangrove Lagoon from the north, covers  $8.8 \text{ km}^2$  (3.4 sq. miles), the largest drainage basin on St. Thomas (Figure 13). A smaller basin, the Nulliberg Basin, drains western slopes of the lagoon and covers  $2.4 \text{ km}^2$  (0.93 sq. miles). Altogether these watersheds drain  $11.2 \text{ km}^2$  (4.32 sq. miles) which is two times the lagoon surface area.

Benner Bay is backed by a drainage basin of  $0.8 \text{ km}^2$  (0.31 sq. miles) and Bovoni Passage is backed by a basin of  $1.5 \text{ km}^2$  (.58 sq. miles). Although these basins are much smaller than the Turpentine-Nulliberg basins, their potential impact on water quality is probably greater because the steep slopes, which are greater than 30 percent, are conducive to rapid runoff. Moreover, the drainage leads directly to the bay shoreline within a short distance.

By contrast, most runoff in Turpentine Run infiltrates the soil and alluvium (Jordan and Cosner, 1973). Only major storm runoff, resulting from rainfalls totaling more than 4 inches, reaches the lagoon as surface flow. Inflow occurs only once every year or two. In August 1963, December 1965 and November 1969,

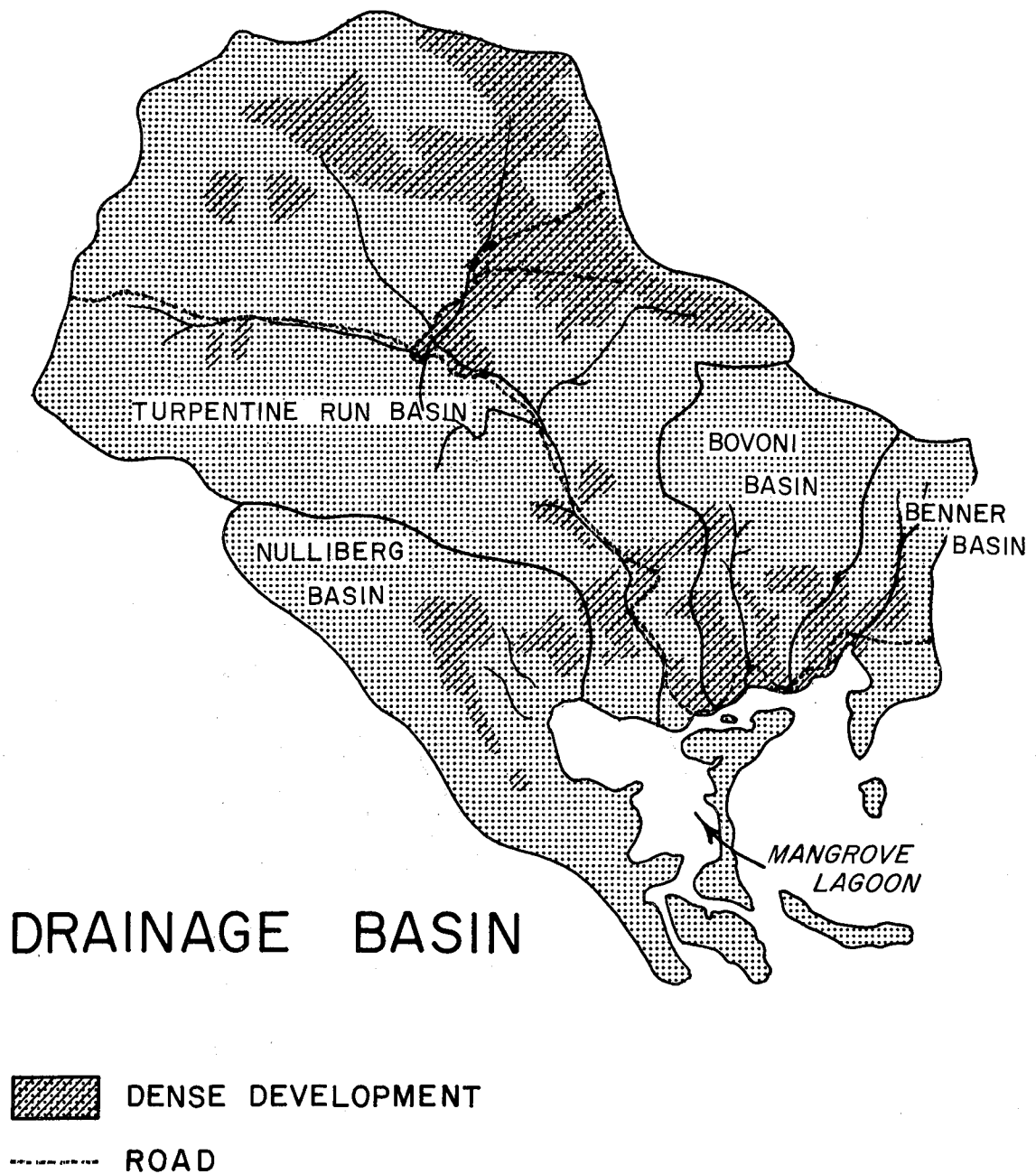


Figure 13. Drainage basins of the Mangrove Lagoon and Benner Bay with areas of dense residence in 1974.

flood flows topped the road at Nadir bridge (Jordan and Cosner, 1973; Towle, personal communication). During these floods, which lasted about 2 - 4 days, discharge into the lagoon amounted to more than 10 million gallons or about  $37,850 \text{ m}^3$  per flood.

Intense development in the upper drainage basin of Turpentine Run, the Tutu area, has increased the potential for flash flooding into the lagoon. By destroying the naturally absorptive soil and vegetation cover with construction of roadways, parking lots and roofs, and by lining stream beds with concrete, flood water from torrential rains is delivered to the lagoon quickly. The impact of stream flooding on water quality is given in a supplemental report.

Since sediment load data for St. Thomas streams is lacking, the influx of suspended sediment must be derived by tenuous extrapolation from representative basins outside the area or from deposition rates in the lagoon itself. Rates of suspended sediment discharge for three small basins in Puerto Rico average 1620 tons per sq. mile per year. At this rate, Benner Bay is supplied with about 1296 tons of sediment, on the average each year. Actually, most sediment is supplied in short pulses during storm of high intensity. If sediment discharged at this rate is spread evenly over the central bay floor, it would amount to a layer only about 6mm thick. Since very little upland sand is found on the bay, the quantity of sand supplied by streams must be limited. Most sediment supplied to the bay is fine-grained silt and clay. By remaining suspended in bay waters

for long periods, the fines degrade water transparency.

The effect of residential development on sediment yield from the watershed is poorly known. Figure 13 shows the location of these developments and Table 4 gives the percentage area occupied by the development in 1974.

Table 4. Drainage basin areas and dense residential areas.

| Basin           | Drainage Basin Area<br>km <sup>2</sup> (sq.mi.) | Percent of Total | Dense Residential Area<br>km <sup>2</sup> (sq.mi.) | Percent of Drainage Area |
|-----------------|-------------------------------------------------|------------------|----------------------------------------------------|--------------------------|
| Turpentine Run  | 8.8 (3.40)                                      | 66               | 2.1 (0.81)                                         | 23.8                     |
| Nulliberg Basin | 2.4 (0.93)                                      | 17               | 0.2 (0.07)                                         | 10.2                     |
| Bovoni Basin    | 1.5 (0.58)                                      | 12               | 0.3 (0.12)                                         | 17.9                     |
| Benner Basin    | 0.8 (0.31)                                      | 5                | 0.2 (0.07)                                         | 26.4                     |
| Total           | 13.5 (5.21)                                     |                  |                                                    |                          |

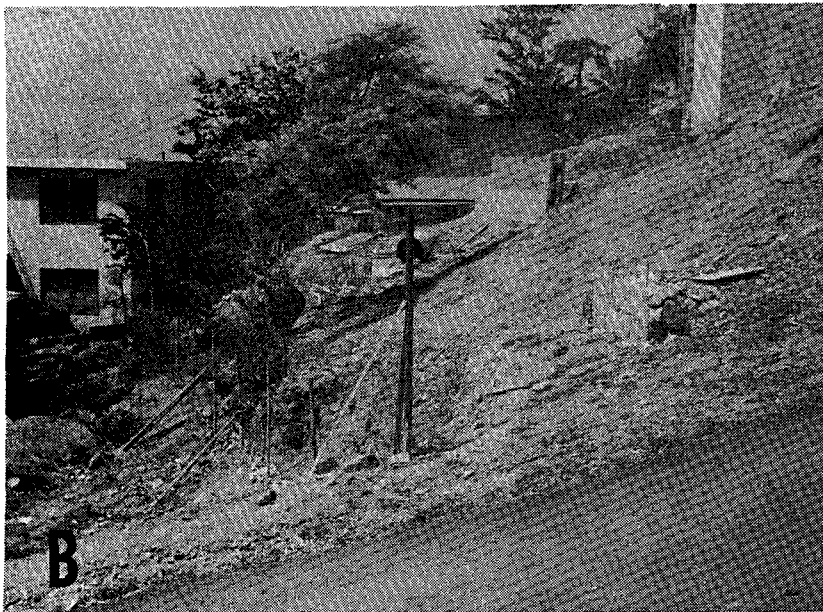
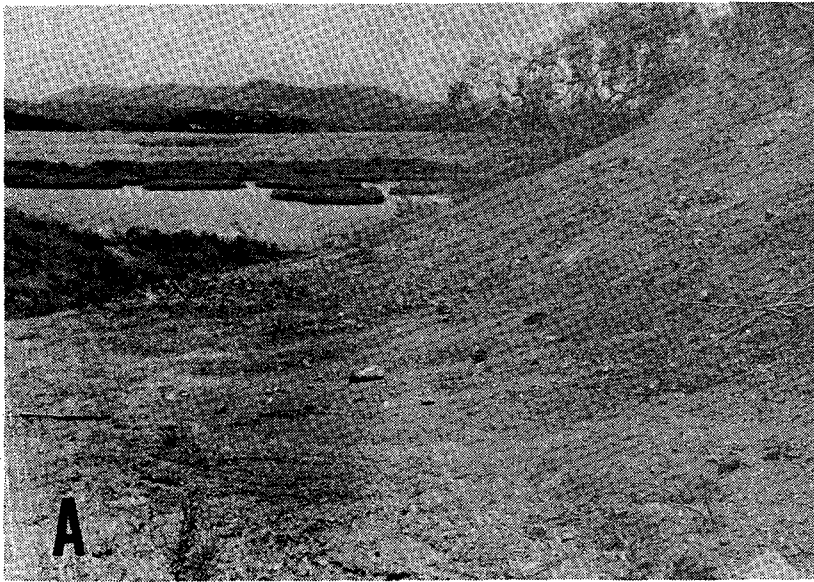
Although some developments have covered the land with impervious surfaces, many backyard slopes and road cuts are exposed to erosion as illustrated in Figure 14. Additionally, large areas of government property west of the lagoon have been stripped of vegetation to provide fill for the municipal dump (Fig. 15).

Impacts from the Benner and Bovoni Basins are probably greater than from the Turpentine Run basin due to the steep slopes, high drainage gradients and erodable character of the soil which has limited permeability. Although development is dense in parts of the Turpentine Run basin and the sediment yield is probably high, the bulk of the sediment is most likely deposited locally in the upland alluvial valleys and has not been transported as far as the lagoon.

Figure 14A. Stripping of vegetation exposes soil to erosion and threatens salt ponds with excess sedimentation. Soil is used by government as fill for municipal dump. View east toward the lagoon and Bovoni Cay.

Figure 14B. Residential development on steep slopes above Benner Bay alters the natural drainage pattern in the watershed and exposes soil to erosion. During high runoff the sediment is washed down guts into Benner Bay temporarily increasing water turbidity.

Figure 14C. Clogged culvert along the shore road restricts drainage into Benner Bay. Roadways disrupt natural drainage when culverting is inadequate to provide for passage of storm runoff.

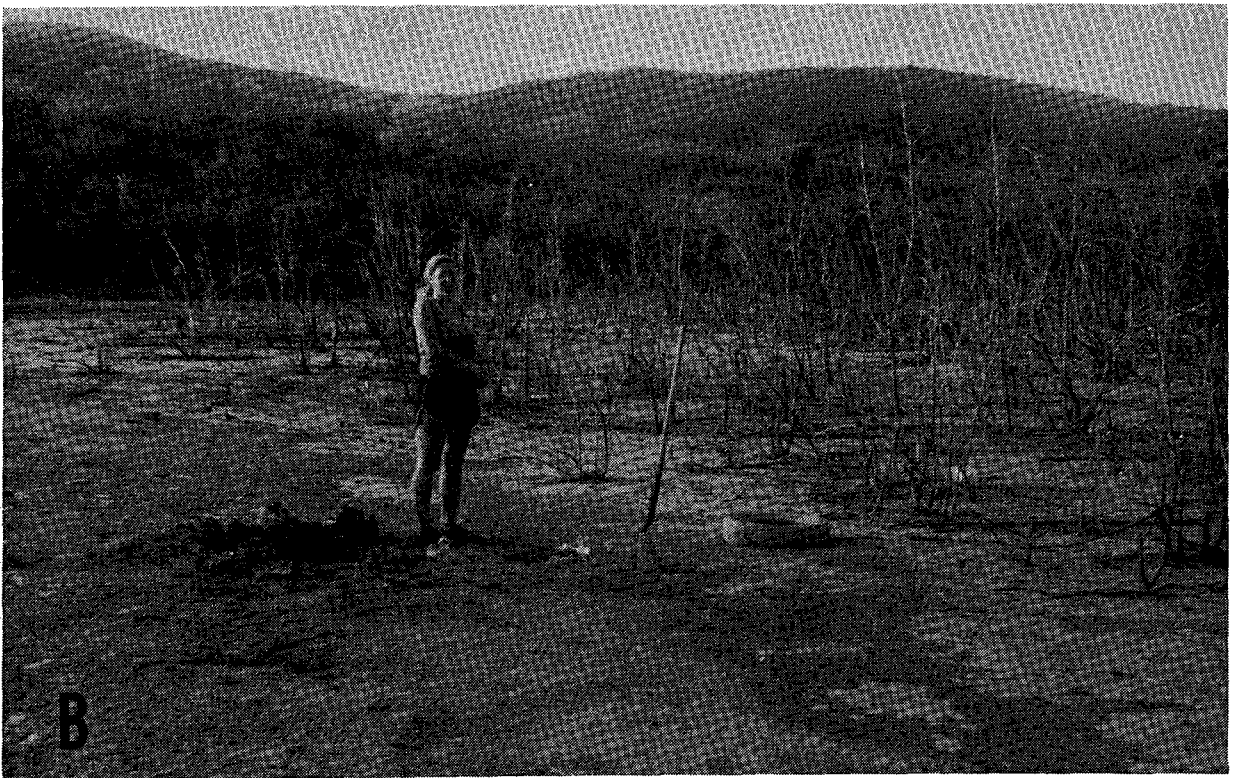




Filling and grading of the extensive racetrack area jeopardizes the quality of runoff supplied to the lagoon (Figure 33). Prior to 1971, flood drainage from Turpentine Run entered the lagoon through two or more vegetated distributary channels across an alluvial delta (Figure 7). These channels acted like a filter to cleanse the runoff of sediments and debris. When the racetrack was constructed on the delta in 1971, drainage was short-circuited through a single channel directly to the lagoon (Figures 6 and 7 ). Thus, the cleansing action of the distributaries has been lost and canalization of the mouth of the run has produced a stagnant backwater.

Figure 15A. Aerial view of municipal dump, August 1977 showing extensive exposure of upland soil and waste disposal areas. Sediment and toxic substances leached from the dump spread lagoonward into Mangroves. Note large zone of dead black mangroves (dm).

Figure 15B. Ground photo lagoonward of municipal dump at point (x) in Figure 15A. Pneumatophores (aerial roots) of black mangroves are partly buried by influx of sediment from the upland. Ground water beneath flats 40-60 cm is highly saline and enriched with toxic metals released from the dump.



7. Geologic Conditions. The lagoon system operates within the confines of a basin which is determined by geologic conditions. These conditions determine the general shape, size and shore characteristics of the lagoon. In turn, they are modified by currents, waves and vegetation and thus acquire different aspects from place to place.

The Mangrove Lagoon is backed on the north and west by low alluvial slopes, whereas on the southwest it is flanked by rock of the Water Island Formations which consists of lava flows, breccias and water-laid tuff which is intruded by dikes. A similar rock formation forms the north shore of Bovoni Passage and it is exposed in eroded cliffs at Compass Point. In a geologic map of the island Donnelly and Whitten (1968) reveal a fault trending northeast-southwest through Benner Bay and the western lagoon reaches near Middle Island. According to the map, the northwest side of the fault is displaced upward relative to the southeast side which is downward. It is possible that a second fault crosses transverse to the first fault at an angle of 45-55 degrees. Such a fault not only would extend the lagoon head to the west but also would account for greater subsidence in the head than elsewhere. All these inferred faults are buried beneath lagoon fill.

The probable relationship between alluvium, rock and buried lagoon sediment is schematized in Figure 16. In this section the slope of the alluvial surface on land and its depth in cores beneath the lagoon deposits projects seaward to the depth of the shelf floor at about 18 m (60 feet). It seems

# GEOLOGIC CROSS SECTION

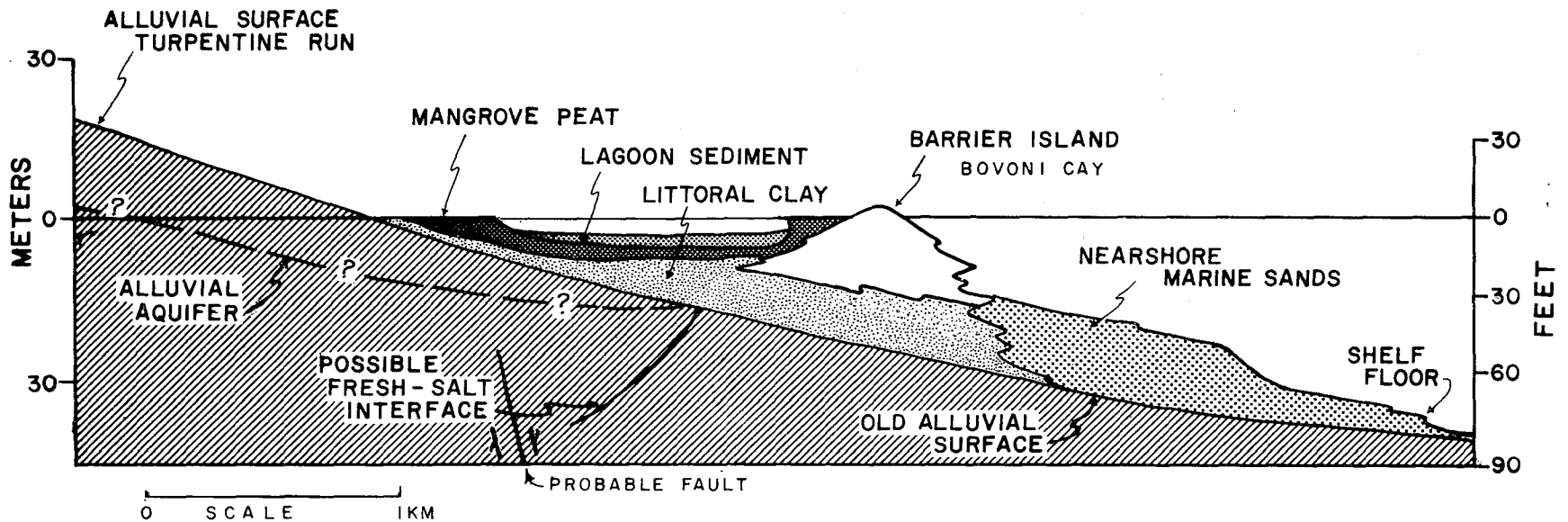


Figure 16. Schematic relationship between major geologic formations across the Mangrove Lagoon.

likely that the ground water aquifer in alluvium beneath Turpentine Run (Jordan and Cosner, 1973) extends seaward beneath the lagoon deposits to the vicinity of Bovoni Cay where it impinges on salty ground water. The relatively impervious clay layer near the base of the lagoon sediments must deter lateral seepage into the lagoon itself and may restrict seaward flow as well. In turn, the clay layer may retard sea water encroachment into wells penetrating alluvium in lower parts of Turpentine Run.

Topographic trends of the old alluvial surface and the thickness of soft or loose lagoon sediment are indicated by the distribution of probe depths (Figure 17). The alluvial surface is relatively shallow along the north lagoon shore, i.e., around the alluvial delta of Turpentine Run, but it is relatively deep along the opposite shore near Middle Island. In Benner Bay the old alluvial surface steepens rapidly away from shore, and sediments exceed a thickness of 15 meters over most of the bay floor. Trends of the old alluvial surface permit tracing probable courses of former streams that were active when sea level was lower about 3400 years ago.

Depositional Units. The layers of sediment cored beneath the lagoon are described beginning with the base alluvium, which extends seaward beneath the lagoon from the upland. Many of the same units are found in vertical as well as lateral sequences. Classification of units is based on gross lithology and visual descriptions.

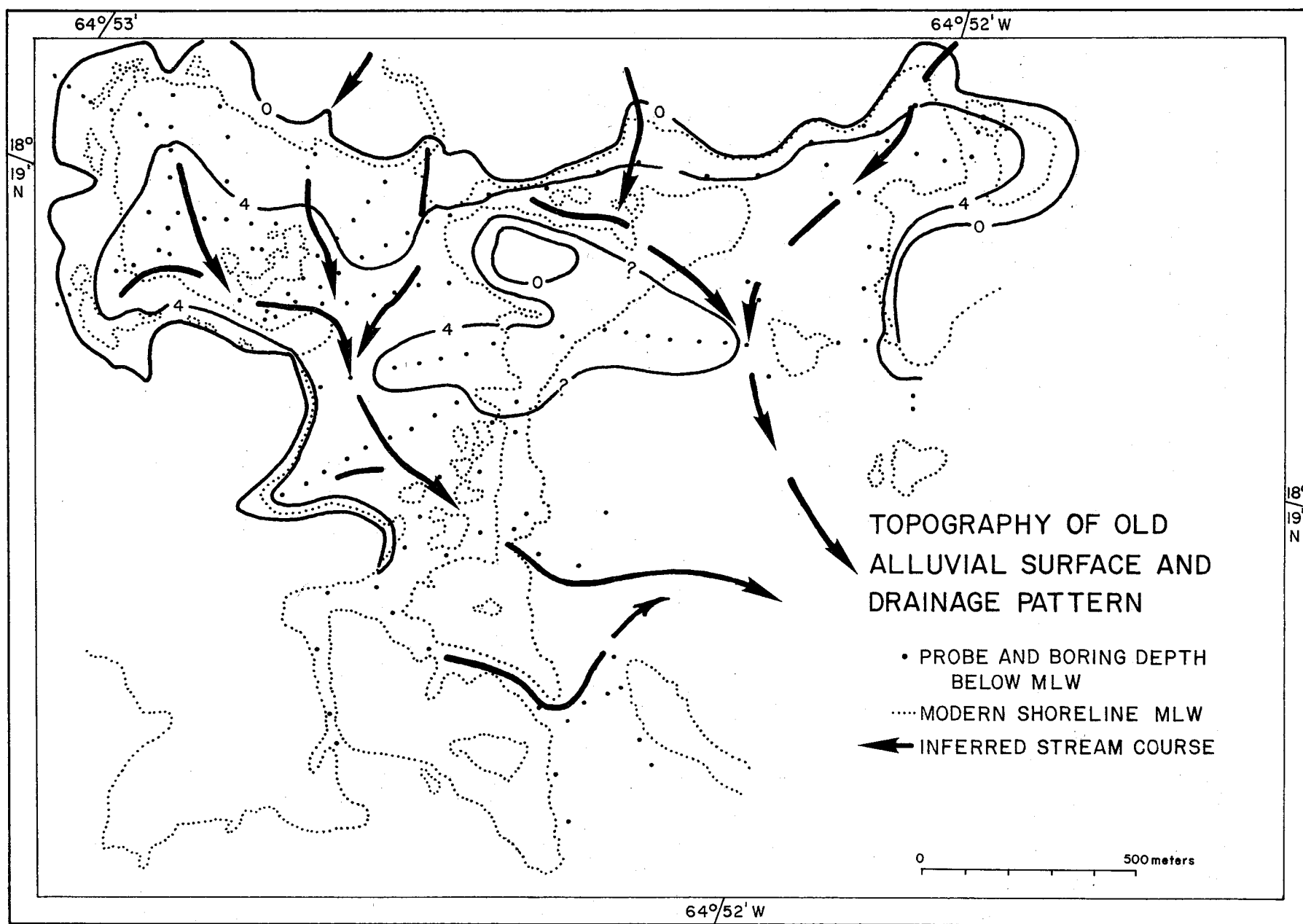


Figure 17. Depth and topography of the old Alluvial surface below mean low water (MLW) in the Mangrove Lagoon and Benner Bay. Arrows represent probable courses of former streams. Solid lines define subsurface contours on the old alluvial surface.

Buried Alluvium. The deepest and most landward unit or facies is a brown to tan sandy clay or clayey sand mixed with rock fragments of terrestrial origin. It is very firm and is non-calcareous except for aggregate cement. It is poorly sorted and structureless and contains Fe-stained particles. Upward it grades into alluvial soils which have many of the same characteristics except it is relatively soft.

High Flats. This unit is not ubiquitous, either on the surface or at depth. It occurs intermittently and is areally limited. The color is mainly brown but often contains dark grey layers. It consists of laminated sandy-clays and clayey sand with calcareous concretions and occasional layers of algal mat in upper parts. Downward it grades into alluvium or alluvial soil whereas upward it passes into black mangrove peaty sediment. This facies contains evidence of bioturbation by crabs and it holds occasional gastropods. The consistency varies from firm to very firm.

Black Mangrove Sediment. A dark greenish grey to grey peaty silt or clay. Root structures are common but not dominant; there is no pure black mangrove peat. Local bioturbation is observed and the samples are all slightly calcareous. The sediment consistency is often soft, due to disintegrated roots forming a muck, but it is occasionally firm near its base where it rests on alluvial deposits.

Red Mangrove Peat. A dark brown and reddish peat, frequently over several meters thick. There are often large living roots throughout the unit and occasionally a matrix of shell or mud. Near the lower boundary it usually blends into clayey and then silty peat. The consistency ranges from spongy to very firm. Living red mangroves normally occur in the lower intertidal zone and red mangrove peat is usually found above black mangrove deposits in vertical sections.

Mangrove Pond Filling. This unit is mainly a contemporary facies which may be represented at depth, but was not observed in any of the cores. It is a black peaty clayey silt or silty clay. In most cases it is soft and contains a high water content. Red mangroves surround margins of the ponds.

Lagoon Nearshore Sediment. At the seaward side of living red mangrove stands and around the inner lagoon margin, there is a distinctive facies consisting of mixed mussel and oyster shell fragments. Halimeda adds to the generally calcareous nature of this sediment. Color and consistency vary widely. These deposits are poorly sorted. At depth they may represent a buried beum deposit.

Lagoon Sediment. Essentially a gray silty clay commonly with a black surface layer 40 to 80 cm thick. Halimeda plates found in the layers give the deposits a sandy character at depth. Shell bits are found in layers and there are shell layers often interbedded with occasionally in Halimeda layers. This facies tends toward homogeneity within layers. It is loose and soft except in shell layers which vary 10 to 20 cm thick.

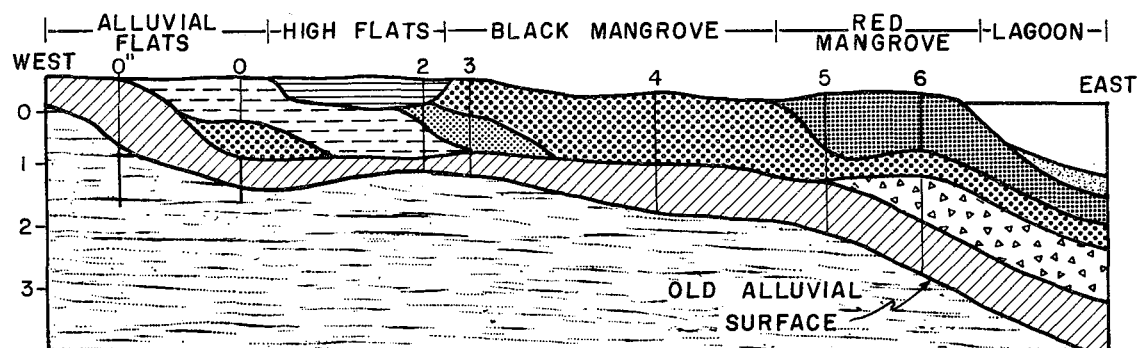
Bluish Grey Clay. This unit is ubiquitous in older deposits as an intermediate sandy clay between the alluvium soils and black mangrove sediments. The bluish grey color is distinctive in fresh samples. It contains calcareous rock fragments but is otherwise structureless, homogeneous and extremely firm. This unit may be a sub-facies of the black mangrove unit or it may have been deposited in ponded backwaters or inner lagoons.

Table 5 summarizes characteristics of the depositioned units encountered in the Mangrove Lagoon and Benner Bay region.

Stratigraphic Sequence. When the buried depositional units are compared from core to core in sections across the inner lagoon margin, vertical and lateral relationships are displayed. Figure 18 illustrates these relationships in a stratigraphic diagram. The surface units, like black and red mangrove peat, can be traced downward in the section from their present site of formation, i.e., in cores 9 and 10, as well as seaward beneath lagoon deposits. Nearshore sediments and high flat sediments however, are very limited in extent. Deposition of these units was probably piecemeal, first here, then there, depending on local conditions controlled by undulations in topography of the old alluvial surface. Nearshore deposits encountered in core 6 suggest a low ridge backed by a shallow trough, cores 4 and 5. By contrast, the extensive peat deposits in the lower section of Figure 18 indicate mangroves persisted in the area continuously from about 4500 years ago to the present day.

The broad relationship of deposits filling the Mangrove

# LAGOON DEPOSITS



- ALLUVIAL FLATS
- LAGOON SEDIMENT
- RED MANGROVE PEAT
- NEARSHORE SEDIMENT, SHELLY
- BLACK MANGROVE PEAT
- BLUISH GREY LITTORAL CLAY
- HIGH FLAT SEDIMENTS
- ALLUVIAL SOIL & FLATS
- OLD BURIED ALLUVIUM
- POND FILLING
- C<sup>14</sup> DATING

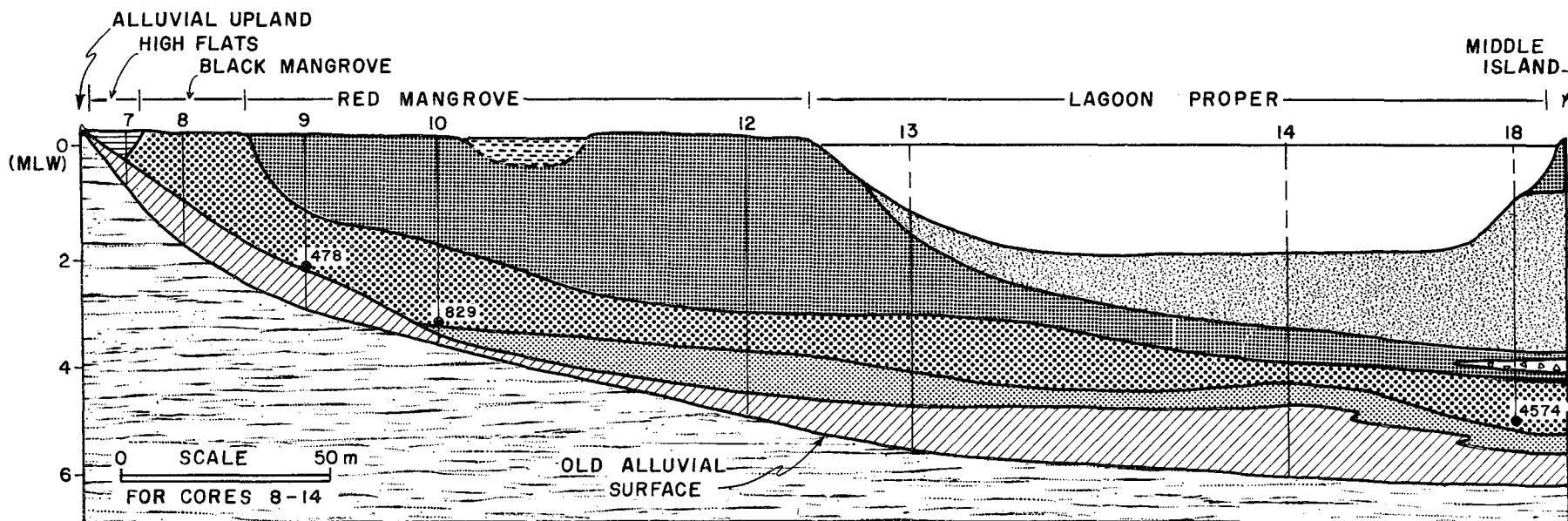


Figure 18. Stratigraphic diagram of depositional units in sections west from the lagoon head (upper) and west from Middle Island (lower). See Figure 3, for locations.

Lagoon depression displays a main transgressive sequence with black mangrove sediments being the main initial unit leading the sequence landward on top of old alluvium. Consequently, sedimentary infilling of the lagoon and growth of Bovoni Cay have proceeded contemporaneously with the rise of sea level during the last 5000 years. In marginal local areas close to land, high sediment supply in the last 200-300 years has turned the landward edge of the transgression into a regression. Such areas include: (1) seaward overlap of high flat deposits on black mangrove sediments or blue clay off the government waste disposal area (Core 7) and west of the sewage treatment plant (Core 2), (2) lagoonward extension of alluvium over high flat and pond sediments at the mouth of the Benner Bay gut (east of Antilles).

Radiocarbon Dating. Radiocarbon dates of intertidal vegetation record the relative rise of sea level that created the lagoon basin. They also provide an estimate of long-term rates of sedimentation. The material dated from the inner lagoon, Figure 18, lower section, consisted of black mangrove roots that today grow downward from just above mean high water to about mean low water or below. It is not expected that roots would penetrate far into the buried soil or old alluvium. Therefore, they mark the intertidal zone for the most part and, in turn, record the position of sea level at the time of their growth. Successive positions of these zones with time and upward accretion of sediment indicate the rate of relative submergence and land-

Table 5. Characteristics of depositional units in the Mangrove Lagoon and Benner Bay area.

| Unit, Facies                        | Color             | Texture                              | Composition                                                                           | Consistency          |
|-------------------------------------|-------------------|--------------------------------------|---------------------------------------------------------------------------------------|----------------------|
| Alluvium (buried and upland)        | brown or tan      | sandy clay, clayey sand              | terrestrial rock fragments; no carbonate except cement in aggregates, Fe.-stained     | very firm            |
| High Flats (Intermittantly flooded) | brown or black    | sandy clay, clayey sand, peaty muck. | laminated algal mats and highly calcareous concretions, gravel and marine gastropods. | Firm to very firm    |
| Black Mangrove (above MHW)          | Black to gray     | peaty clay or silt,                  | highly calcareous, disintegrating root structure, bioturbation                        | soft to firm         |
| Red Mangrove (Intertidal)           | Dark red to brown | peat                                 | large roots in mud or shell matrix                                                    | spongey to very firm |
| Mangrove Pond                       | black             | peaty, clayey silt, silty clay       | often calcareous, high organic content                                                | soft                 |
| Near Shore (1m below MSL)           | varies widely     | very poorly sorted                   | shell fragments, <u>Halimeda</u> , bits of wood and peat                              | varies soft to firm  |
| Lagoon                              | black to gray     | silty clay                           | shell fragments and <u>Halimeda</u> in layers                                         | soft                 |
| Blue clay                           | blue              | clayey sand                          | rock bits, highly calcareous, terrigenous sand                                        | extremely firm       |

ward transgression. These elements serve as a geologic norm against which rates of recent sedimentation can be compared and evaluated.

The position of the radiocarbon dates in relation to a line of average sea level rise, based on dates from the U.S. East Coast, is shown in Figure 19. Dates from near the base of cores 9 and 10 indicate relatively rapid subsidence and rapid sedimentation, 33 cm per century (13 inches per 100 years). This rate is more rapid than during the period 4,500 - 900 BP as indicated by the slopes of the line from core 18 to core 10. On the other hand, the date in core 26 from Benner Bay lies at a relatively shallow depth (3.6 m) for its age. This suggests very slower rates of submergence than normal, a rate possibly affected by relative uplift, during the last 5000 years.

Table 6. Radiocarbon age and depth of subsurface samples from the Mangrove Lagoon and Benner Bay. Dates determined by Geochron Laboratories.

| Sample  | Depth below MLW, cm | Sample Character           | Radiocarbon Age |
|---------|---------------------|----------------------------|-----------------|
| Core 9  | 165 - 185           | Peaty clay, Black Mangrove | 460 $\pm$ 145   |
| Core 10 | 280 - 300           | Peaty clay, Black Mangrove | 805 $\pm$ 140   |
| Core 18 | 495 - 520           | Silty Peat Black Mangrove  | 4445 $\pm$ 185  |
| Core 26 | 360 - 370           | Red Mangrove peat          | 5005 $\pm$ 175  |
| Core 39 | 68 - 73             | Peaty sand (Red Mangrove)  | 995 $\pm$ 190   |

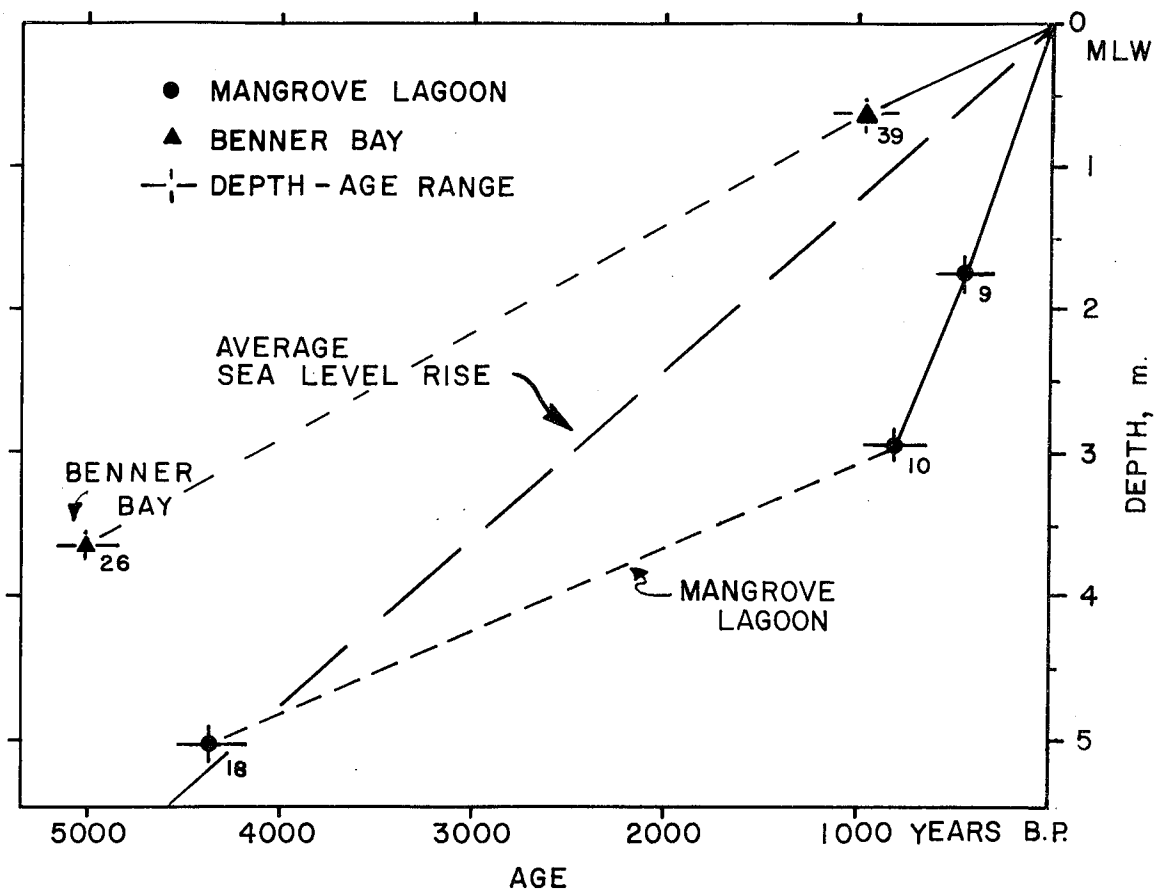


Figure 19. Age-depth graph showing position of radiocarbon dates of samples from the Mangrove Lagoon and Benner Bay in relation to an average sea level line for the U.S. East Coast.

Geologic Development. By integrating the information from probes, cores and radiocarbon dates, a sketch of the recent geologic evolution of the lagoon is revealed. The lagoon occupies a basin originally downfaulted and partly excavated by the ancestral streams of Turpentine Run. When sea level was lower prior to 5000 years B.P. the streams flowed through valleys to a shoreline located farther seaward on the present-day shelf. By 5000 years B.P. (before the present), the global sea level rise inundated the valleys forming broad estuaries divided by an interfluvial alluvial delta (Figure 20A). Spits formed across the entrances and mark the former shoreline, which lies along the present-day 6-meter (18 foot) depth curve.

Continued rise of sea level between 5000 and 2000 B.P. flooded most of Jersey Bay (Figure 20B). As waves reworked the bay floor and former delta deposits, a barrier island, Bovoni Cay, formed. This, together with reefs and cays to the west, isolated inner waters forming a lagoon with broad passes at entrances and between estuary margins of the lagoon, mangroves extended landward over broad lowlands and grew upward with the rise of sea level.

By the time the sea approached its present level (Figure 20C), 500 - 200 B.P., sands of Bovoni Cay were moved westward by longshore currents and landward by storm washovers. The Cay and adjacent shoals were quickly stabilized by mangrove growth, accreted landward and coalesced into a nearly continuous barrier island. Mangroves also have stabilized the seaward side of

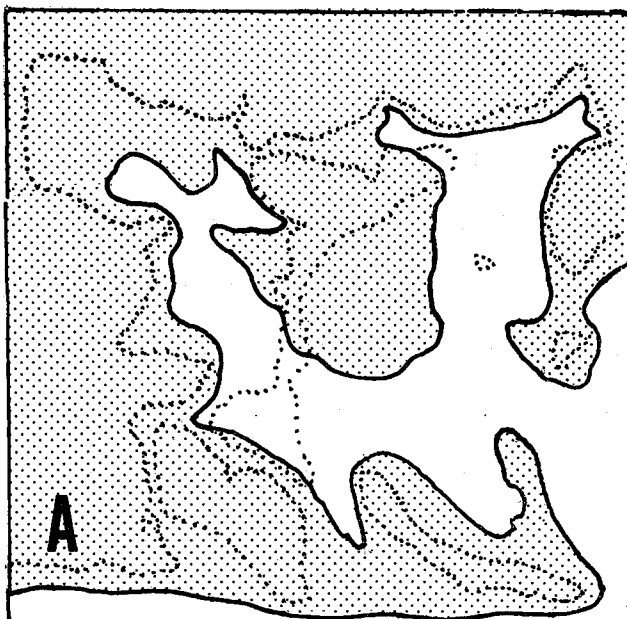
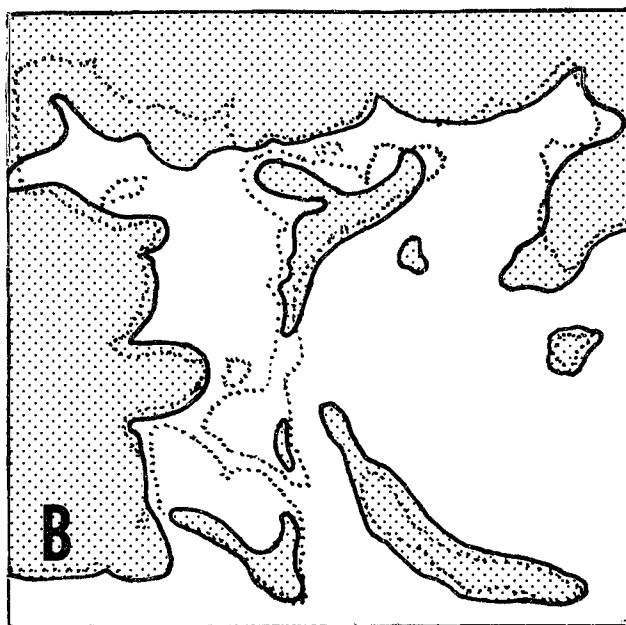


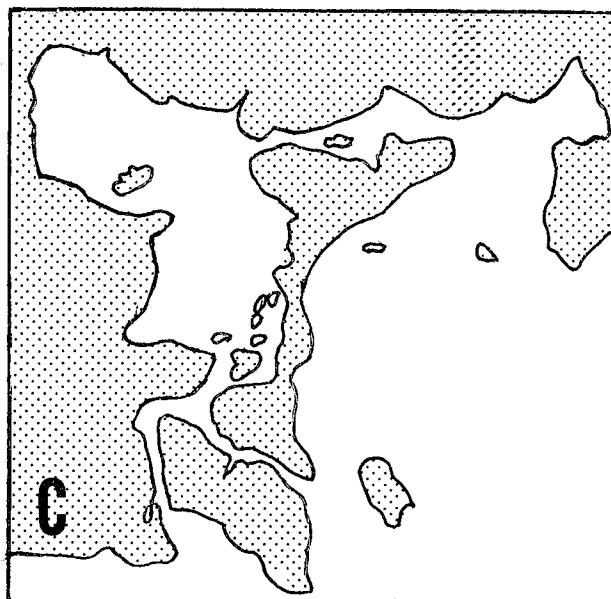
Figure 20. Probable geologic evolution of the Mangrove Lagoon

A. Drowned estuarial embayment about 5,000 years (BP) before the present.



20B. Rise of sea level, formation of Bovoni Cay, Patricia Cay and lagoon with fringing mangroves, 5000 to 2000 B.P.

20C. Continued rise of sea level and expansion of mangroves, 500 to 200 B.P.



Bovoni Cay and therefore cause it to prograde seaward at several points. A small barrier which formed along the exposed inner (west) lagoon margin isolated backwaters into inner lagoons and ponds. Segmentation of the lagoon continues to the present-day as exemplified by formation of Middle Island and the shoal between Middle Island and the entrance to Bovoni Passage.

Because the geologic history has been so long and complicated, sedimentary substrates are highly variable in the area. Environmental management must consider this fact and know the nature of the geologic variations.

## 8. Environmental Conditions

Waves. Of the different energy sources affecting the lagoon, waves, tide, wind and stream inflow, waves provide the chief driving force. By breaking on the reefs around Patricia Cay, they set up a local head of water which drive a mass transport of water across the reef and into the lagoon. When winds reach more than 7 m per sec (14 knots), they create an internal wind drift within the lagoon and thus dominate over tides as a driving force. By contrast during periods of light weather when sea swell is low, the long-continued action of the tide is relatively important. Therefore, with time the lagoon is stressed by different but interrelated energy sources. They act either in combination to produce an additive stress, or opposed to cancel each other.

Commonly, ocean waves approach the coast from the east-southeast. They are refracted into the Jersey Bay from the southeast by landward shoaling of the Bay floor and by the seaward end of Cas Cay which forms a projecting headland receiving the brunt of wave attack. Such waves are generated by the northeast trade winds. Typically, they have a height of 0.3 - 1.0 meters (30-60 feet).

As the waves enter Jersey Bay, they "feel bottom" and are refracted into gently-curved patterns with crests more or less parallel to the bottom contours (Figure 21). Bending of the crests is incomplete, however, for along the northeast shore of Cas Cay, they break at an acute angle to the shore while along

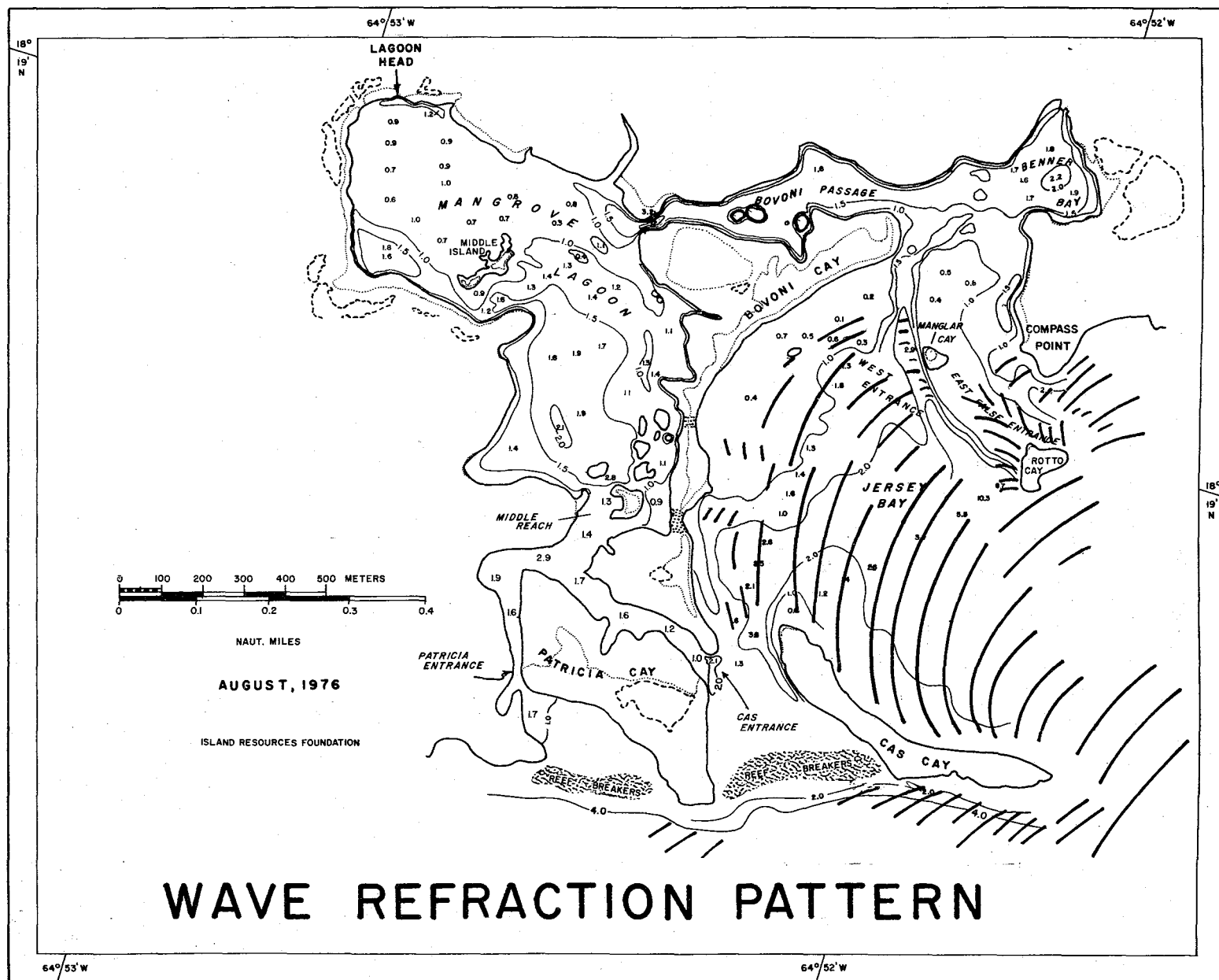


Figure 21. Wave refraction pattern for easterly swells reproduced from NOS aerial photographs of 1958 and 1974.

Manglar Cay they run transverse to the shore. Shoals in central Jersey Bay along the 1-meter depth contour tend to hold back advancing waves. The resulting frictional effect on the bay floor produces "blowouts" which expose sand beneath an eroded sea grass cover. Blowouts are observed in water depths from 1.0 m to 3.6 m (3 to 12 feet). By contrast, the West Entrance channel and the trough leading to Cas Entrance allow the waves to penetrate somewhat farther landward than on the shoals, but their height is greatly reduced, less than 6 cm (0.2 feet). Because of the narrowness of the West Entrance channel and protection provided by Manglar Island and adjacent shoals, waves do not enter Benner Bay under normal conditions. Bovoni Cay excludes waves from the Mangrove Lagoon proper. Additionally, mangrove prop roots effectively buffer the shore by absorbing wave energy and they retard shore currents.

Ordinary wind waves driven by east or northeasterly winds across the Mangrove Lagoon are small because of the short fetch and relatively shallow bottom. They vary in height from ripples to 25 cm (0.8 feet). However, during local squalls and storms they increase to 40 cm or more; muddy sediment is stirred up increasing the turbidity more than two-fold. Wind stress also drives water westward creating a set-up along the western shore. The excess water is either driven landward into backwater ponds and flats, or for another part, it returns eastward through the passage between Middle Island and the western shore.

Storm Waves and Tidal Flooding. Although Bovoni Cay and the mangrove forest provide substantial protection from most storm

waves, the lagoon and bay are susceptible to tidal flooding created by major hurricanes. Such hurricanes, which have a frequency on the average of once in 33 years, raise water levels about 1.5 meters (5 feet). This would flood most marinas and shorefront facilities in the area. It would inundate lowlands northward to the Nadir-south coast road and westward to the drag race track. It would threaten the sewage treatment plant and present serious problems of lagoon contamination.

Tides. Rise and fall of the tide is relatively small in the lagoon and bay, less than 30 cm (1.0 feet) most of the time. Mean range, determined from 5 months of NOS record between November 1, 1972 and April 4, 1973 on a gauge along Bovoni Passage (Figure 2), is 27 cm (0.9 feet). The highest extreme tide accompanying common storms was 47 cm (1.59 feet) above mean low water, whereas the lowest water was 7 cm (0.25 feet) below mean low water.

Character of tidal fluctuations at Benner Bay during a month follows the predicted tide for Charlotte Amalie. The time of high water is 18 minutes earlier at Benner Bay than at Charlotte Amalie whereas the time of low water is 10 minutes later on the average. Although the tide changes character through a month, it is predominately of the diurnal type; that is, there is one high water and one low water each day. Part of the time the tides are of the mixed type.

Within the lagoon and bay, tidal differences from place to place are small. Differences in the time of high and low water observed one to two days on staves at Bovoni Passage, Cas Entrance and at the lagoon head, are less than 30 minutes. Differences in

range obtained from 31 days of tidal record averaged 1.8 cm (0.06 feet) lower in the lagoon than at Cas Entrance (Michel, 1970).

Superimposed on daily and semi-diurnal fluctuations of the tide there are seasonal changes in which the monthly mean low water is lower in winter and spring than in later summer. During low levels reef crests are exposed to a greater extent and thus the influx of ocean water to the lagoon is limited. As shown in Table 7, monthly mean low waters were as much as 13.4 cm (0.44 feet) lower in January than in July, 1976. Additionally, they were 8.1 cm lower in March and April, 1976 than during the same months in 1975. Anomalously low values, about 12 cm below normal, occurred in May and June, 1976, prior to the present survey. The normal seasonal variations have long been noted in the Caribbean region. They are ascribed to seasonal changes in wind and weather conditions. Low seasonal levels not only restrict transfer of ocean water across the reefs into the lagoon but they also restrict flow into ponds and backwaters at a time when evaporation is high. Thus, the ponds are either very poorly flushed or entirely dried up.

The volume of water entering and leaving the Mangrove Lagoon on each tidal cycle, mainly once a day, called the tidal prism, varies a great deal from neap to spring tide range. However, on the average, the monthly mean tidal prism is 191,238 cubic meters (6,752,613.7 cubic feet; Table 1). The mean tidal exchange in the lagoon amounts to 19 percent of the total volume of water below mean high water, 996,193 cu. meters. The corresponding tidal exchange in Benner Bay amounts to 18 percent.

Table 7. Comparison of monthly mean low water tidal heights at Charlotte Amalie, 1975 and 1976, data from National Ocean Survey. ---Indicates no data available.

| Month    | 1975 Monthly MLW |         | 1976 Monthly MLW |         | Height Difference 1975-76 |
|----------|------------------|---------|------------------|---------|---------------------------|
| January  | ---              | ---     | 99.4cm           | 3.26ft. | ---                       |
| February | 106.7cm          | 3.50ft. | 100.0cm          | 3.28ft. | -6.7cm                    |
| March    | 111.0cm          | 3.64ft. | 103.4cm          | 3.39ft. | -8.0cm                    |
| April    | ---              | ---     | 103.7cm          | 3.40ft. | -8.2cm                    |
| May      | ---              | ---     | 99.7cm           | 3.27ft. | ---                       |
| June     | ---              | ---     | 101.8cm          | 3.34ft. | ---                       |
| July     | ---              | ---     | 112.8cm          | 3.70ft. | ---                       |
| August   | ---              | ---     | 111.9cm          | 3.61ft. | ---                       |
| December | 101.6cm          | 3.33ft. | ---              | ---     | ---                       |

At neap tide range, tidal exchange may amount to only 3.5 percent, whereas at spring tide range it may reach 38 percent of the total volume of water. Because of varying size and "conductance" capability of the different entrances, most tidal flow, about 65 percent, is transported through the Cas and Patricia Entrances while the remainder, 35 percent, is transported through the entrance to Bovoni Passage.

Although tidal forces are small compared to wind and wave transport over the reef, they are the most persistent force over the long-term. They are also the main force during periods of light weather, a time when "worst case" conditions for exchange and flushing of pollutants develop.

Tidal Boundary Demarcation. The intersection of tidal datum planes with the shore around the Mangrove Lagoon and Benner Bay was observed at 18 points. From these "check points" the horizontal positions of the mean high and mean low water lines were drawn on an aerial photograph enlargement using vegetation patterns as a guide.

The tidal datums were derived from NOS tidal bench marks based on five months of record between November 1, 1972 and April 4, 1973. During this time the monthly mean low waters in the region are commonly about four centimeters lower than average for a year. For this reason, and because the tide data are of relatively short duration, the tidal datums are necessarily preliminary. Observations of the water line were made by two to three crews during a diurnal tide, within  $\pm 30$  minutes of mean high and mean low water on a reference staff in Bovoni Passage.

Results of the observations and boundary demarcation are compiled in the bathymetric chart of Figure 8. The mean low water line, or primary shoreline, on the chart commonly lies along the upper part of the red mangrove prop root mass as shown in Figure 38. The intersection surface consists of root masses, organic debris or peat. Horizontally, as viewed in plan view on an aerial photograph, the mean low water line lies landward of the seaward edge of mangrove branches at distances from 0 to 7.5 m. At one point on the north end of Manglar Cay a distance of 54.6 m was recorded. The mean high water line lies from 1.5 to more than 100 meters landward of the seaward mangrove edge. This is often close to the landward limit of red mangroves or the boundary

between red and black mangroves. Most Manglars are below mean high water except central parts of Manglar Cay and Middle Island (Figure 8). Because tidal flow is restricted in semi-enclosed areas, ponds and inner lagoons, the datums vary and thus limit demarcation.

Tide levels are important for defining dredging planes as well as horizontal boundaries. It would be useful to obtain tidal height measurements for a year or more and to relate the derived datum to long-established tidal datums for Charlotte Amalie harbor. Tidal data are crucial for establishing legal boundaries in rapidly growing shorefront areas. A knowledge of storm tide levels is often required for insurance as well as for planning new construction.

Circulation. Current patterns exhibit considerable variety in time and space. Measurements reveal four modes of circulation driven by different forces: (1) a broad clockwise pattern driven by mass wave transport which is directed inward through Cas Cay entrance and outward through Benner Bay; (2) a reversing tidal current; (3) a local wind drift; (4) a stream runoff flow seaward through both entrances. The current speed and direction and a particular time and place is the resultant of components derived from the different driving forces. Because the lagoon and bay have variable entrances, geometry must be taken into account.

Of the four circulation modes the broad clockwise mode is most distinct (Figure 22A). As ocean waves are refracted and break on the Patricia and Cas Cay reefs, the mass transport over the reef builds up a local hydrostatic head. This head forces water partly into Jersey Bay and for another part into the lagoon. More water enters Cas Entrance, which has a relatively larger cross sectional area of flow than Patricia Entrance which has a small entrance choked with Porites rubble (Figures 10 and 22). As water passes inward and spreads out through middle reaches of the lagoon, velocities diminish from 0.10m per sec to less than 0.04m per sec. In the central lagoon, part of the flow moves slowly westward in a counterclockwise gyral around Middle Island. Another part moves eastward through Bovoni Passage and out the Benner Bay West entrance. A maximum velocity of 0.14m per sec was recorded in the narrow part of Bovoni Passage which acts like a nozzle. Interestingly, bottom water often moves westward through the "nozzle", opposite to the predominate eastward surface current. This feature is a

response to small water level differences between the lagoon and Bovoni Passage. The travel time for a parcel of "new" water from Cas Entrance and to Benner Bay West Entrances is about 20 hours.

A distinctive feature of the wave-driven circulations is its wide range in speed with time. The flow "pulsates" through passages. Such a feature may relate to mass transport of waves in groups as they break on the reef. Around Benner Bay and Manglar Island both current speed and direction are highly variable with time.

The wave-driven circulation provides an influx of relatively clear ocean water through Cas Entrance and a discharge of turbid lagoon and passage water out Benner Bay West Entrance. Evidence of turbid discharge is clearly seen on the aerial photo, Figure 6, at point "p" whereas the bottom features are clearly visible in southern and middle lagoon reaches of the 2 meter depth "ML" (Figure 6). When the wave-driven circulation and associated mixing is active, gradients of salinity and temperature between the lagoon and Jersey Bay are small. Water quality overall is improved.

Tidal currents create a reversing circulation pattern, i.e., landward during the rising tide and seaward during a falling tide (Figure 22A). The narrow reach of Bovoni Passage tends to segment the ebb flow inasmuch as this passage has a lower flow "conductance" than Cas Entrance. Like the wave-driven currents, speed of tidal currents generally diminishes inward. Most lagoon tidal currents are less than 4cm per sec. They provide minimal circulation and mixing during semi-diurnal tide phases, but during diurnal phases

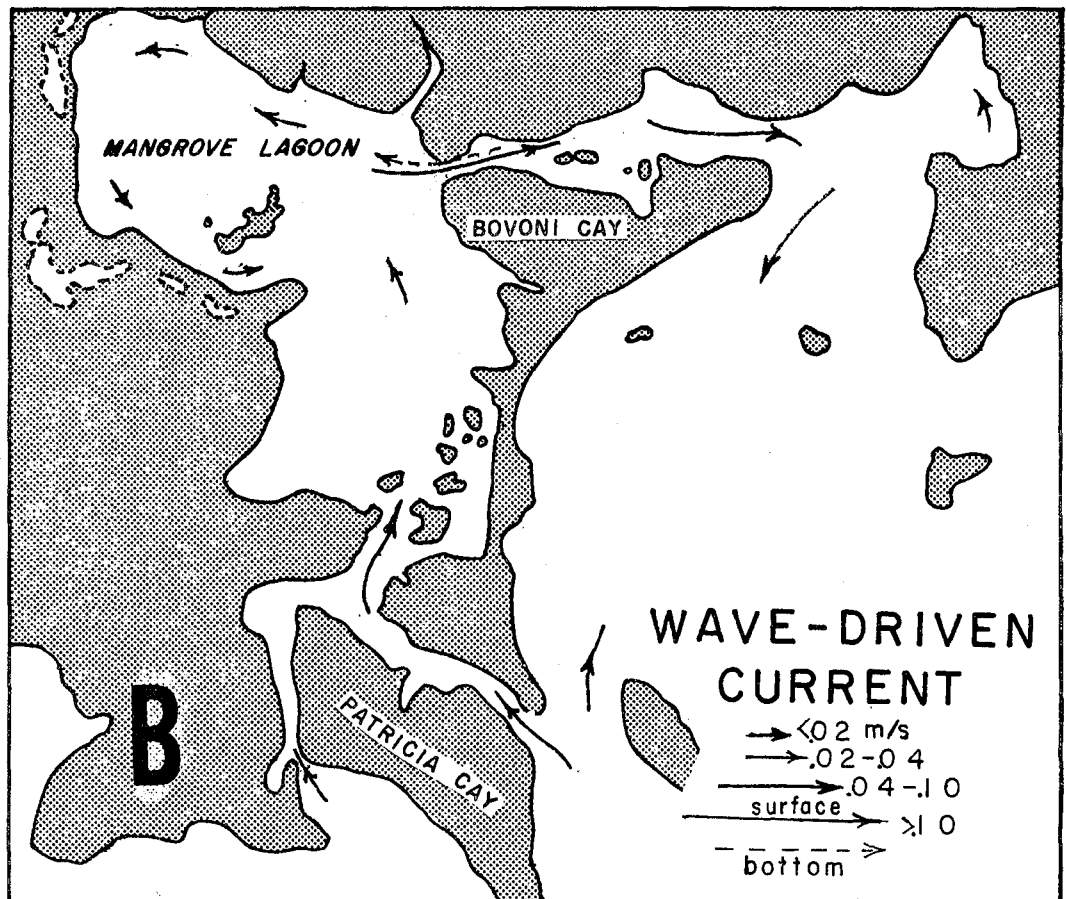
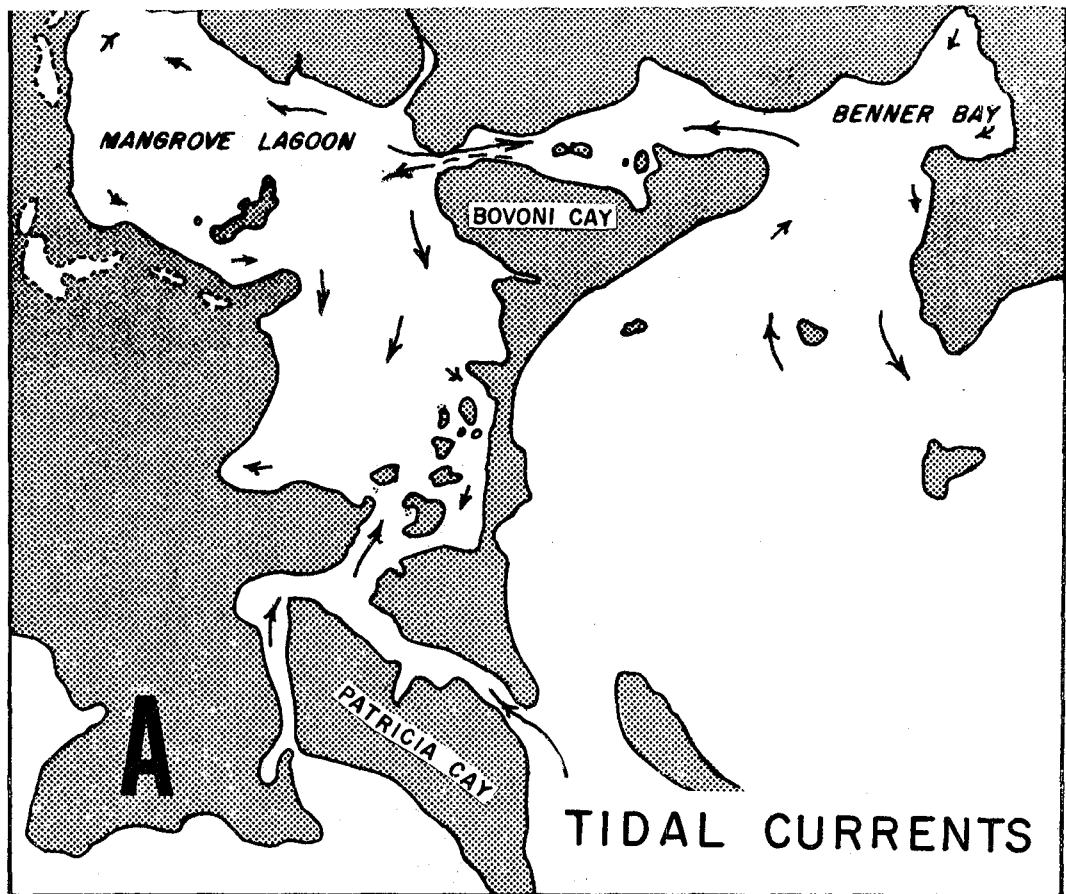


Figure 22. Surface currents based on anchor stations and dye patch observations, August 1976. A. Tidal currents August 25-27, during rising tide. B. Wave driven transport, August 17-19.

they create a significant circulation. Tidal currents are the most important mode of circulation during periods of low wind and waves on the reefs.

Wind drag over across open reaches of the inner lagoon produces a local wind drift of near-surface water. Under conditions of easterly trade winds blowing greater than 7m per sec (14 knots), the drift flows westward across the middle and inner lagoon. This drives water against the western shore with speeds of 2 to 3cm per sec. Part of the water returns eastward south of Middle Island where it is dampened in a null zone of opposing easterly wind drift. Since wave transport over the reef is also driven by the wind, the local wind drift is commonly superimposed on the broad clockwise circulation.

Currents driven by stream runoff are significant during short periods of flooding. Although they have not been measured directly, they are reported by fishermen and their effects are indicated by salinity and turbidity distributions (Grigg et al, 1971). For example, a 5-inch rainfall over Turpentine Run and Nulliberg Basins discharges an estimated 76,000 m<sup>3</sup> per storm (3 days) which amounts to an outflow of 0.36 m<sup>3</sup> per sec through lagoon entrances. This results in an average outflowing current of 0.15cm per sec. Since this circulation disperses mud and land-borne debris with contaminants, throughout the lagoon, it is detrimental to lagoon ecology.

Most currents, except for stream runoff, are essential to maintenance of good ecological conditions. Currents bring in clean sea water from Jersey Bay, they redistribute nutrients from mangrove,

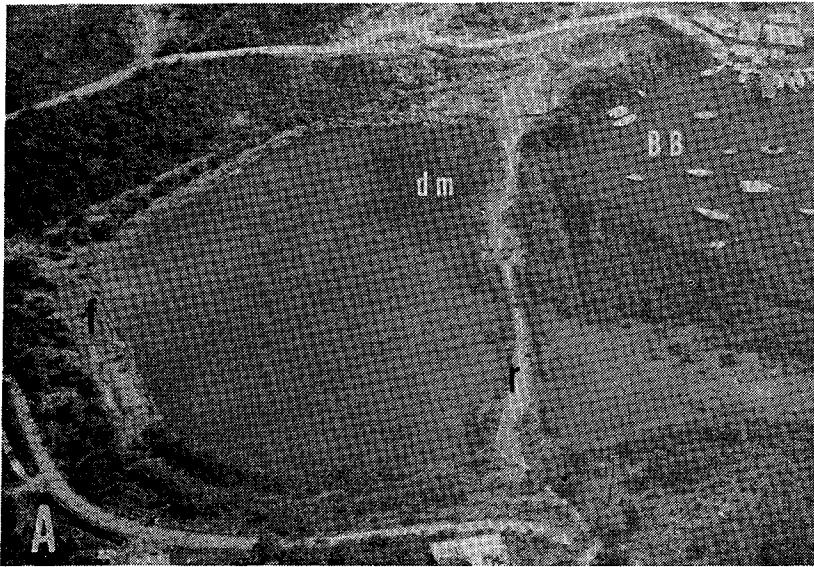
disperse larvae of fish and shellfish, mix and dilute turbid lagoon water, partly flush contaminants out and perform many useful functions. Without a circulation the lagoon would become a stagnant dead lake. Such conditions already exist on a small scale in most marginal salt ponds around west, north and east parts of the lagoon and bay.

Drainage and tidal exchange of the salt ponds with the lagoon is restricted by road fill, landfill, debris, trash and growth of mangrove prop roots (Figures 23A-C). The restrictions are most effective during periods of neap tide range and low seasonal tides from December through May. This is also the dry season. Consequently, high evaporation in restricted ponds at this season leads to extreme salinity in soil and surface water. Mangroves suffer or die (Figure 23C, see section on mangroves for details). Additionally, sediments become black and anoxic; water quality is degraded by extreme diurnal oxygen content. Closure of the ponds reduces the area of tidal flooding and therefore lowers the tidal prism and flushing rate. Closure of the Compass Point salt pond east of Benner Bay by road fill has reduced the tidal prism of inner Benner Bay by about 33 percent. In turn, flushing of the inner bay is reduced about 20 percent further extending the residence time of pollutants.

Figure 23A. Aerial view south across the Compass Point salt pond, August 1977. Zone of living mangroves (lm) flushed by tides of Benner Bay (BB) contrasts with zone of dead red mangroves (dm) in the salt pond which is restricted by road fill (r). Landfill along inner margin of pond (f) replaces a former fringe of mangroves. It restricts drainage from the land and is a local source of turbidity.

Figure 23B. Ground photo of road fill across the Compass Point salt pond at the head of Benner Bay, August 1977. By restricting drainage and tidal exchange between the pond and the bay the volume of water for flushing pollutants in the bay is reduced and a natural nursery area for juvenile fishes is destroyed.

Figure 23C. Restricted drainage between salt ponds along western lagoon shore near sewage treatment plant, March 1977. Low tides and high evaporation during this season lead to stagnation and extreme surface and soil salinity. Many black mangroves are dead or dying.





### Water Quality

The value of lagoon waters is derived from a combination of physical and chemical properties that benefit man and biota. The results are directed to finding the sources of pollution and establishing guidelines for improving water quality.

The distribution of different water quality parameters is illustrated in the chartlets of Figures 24, 25, 26 and 27. These provide information on a seasonal basis; they are supplemented by other data obtained by the DCCA Water Pollution Lab during intervening periods.

Temperature measurements reveal nearly isothermal conditions throughout the lagoon and bay most of the time. In summer, lagoon waters are about 2°C warmer than seawater in Jersey Bay. In winter lagoon waters are about 2°C cooler than in Jersey Bay. Thus, the annual range of temperature in the lagoon is greater than in the adjacent bay. On an annual basis water temperature in the lagoon tends to follow variations of air temperature because the waters are so shallow and vertically mixed. The seasonal trends of temperature in Benner Bay are shown in relation to open south coast bays, in Figure 28.

Extreme temperatures, greater than 35°C, were recorded from backwaters and salt ponds that have restricted circulation. Such extreme temperature variations limit the number and distribution of plant and animal species in these areas.

With increasing turbidity and suspended material in lagoon waters which is dark and absorptive, and with gradual shoaling of the lagoon floor, maximum water temperatures may be expected to increase with time. Thus, conditions for plant and animal life will become more rigorous and some species eliminated.

Salinity data indicate that lagoon and Benner Bay waters are neutral from August 1976 to January 1977, and slightly hypersaline from February 1977 to May 1977. Measurements from ponds and backwaters are extreme, either nearly fresh following local rainfall or distinctly hypersaline, greater than 50 ppt. during drought, see Table 11 for mangrove pond salinities. Strong differences in salinity occur locally where pond drainage enters the lagoon.

Long periods of drought and hypersalinity, particularly between February and May when the tidal plane is low and mass transport over the reef is limited, lead to worsening conditions for pollution. Not only does evaporation concentrate materials but it leads to a net inflow of water. Thus, particulate pollutants accumulate in inner reaches and few escape seaward.

Although the range of salinity is relatively narrow throughout most of the lagoon and in Benner Bay both vertically and horizontally, it is often critical to growth and reproduction of certain species that have evolved in harmony with chang-

ing salinity. Some species have undoubtedly adapted to the alternating pattern of neutral and hypersaline water which is temporarily interrupted by freshwater runoff. It is presumed that the natural salinity regime provides optimum functioning of life in the lagoon. For management it is important to maintain open entrance reaches and to control development that restricts flow.

Dissolved oxygen concentration varies over a wide range in the lagoon and Benner Bay whereas in seawater of Jersey Bay it varies within narrow limits. Concentrations reached an early morning minimum of 1.6 mg/l near the lagoon head in August 1976. By contrast, a mid-afternoon peak of 12.6 mg/l was recorded. These values contrast with a range of 5.6 to 6.9 mg/l in seawater of Cas Entrance.

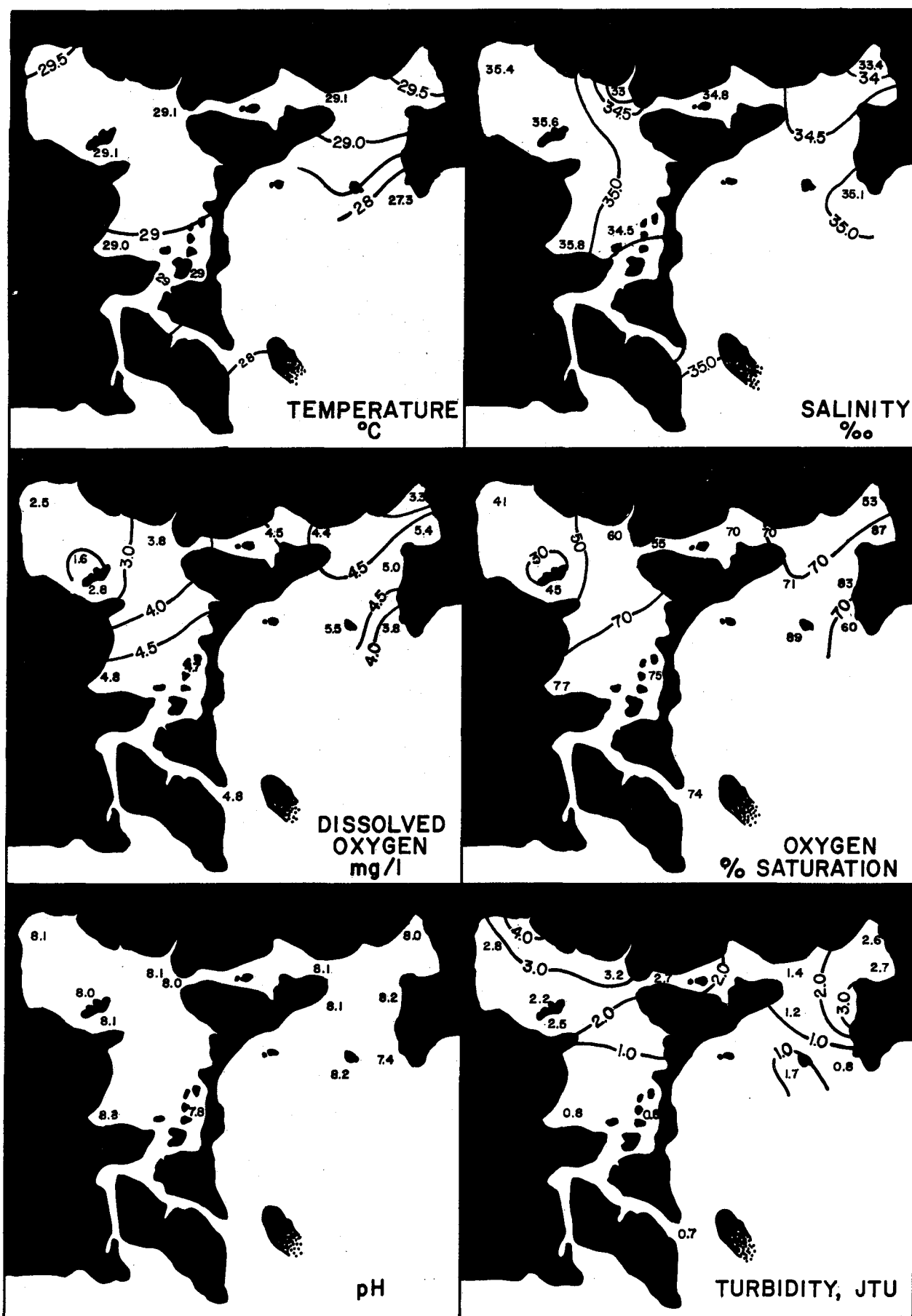
Besides the large diurnal range in polluted and plankton-rich water, percent oxygen saturation remained below 100 percent more than 65 percent of the time. This suggests at first an excess of oxygen consumed by respiration over oxygen produced by photosynthesis. However, once the metabolic rates are corrected for oxygen diffusion into or out of the water, and when changing rates of respiration or photosynthesis are taken into account, the actual metabolic rate, or community metabolism differs.

On an annual basis oxygen values were generally lower during August, September and October than in January, February

Figures 24, 25, 26, 27, which follow on the successive four pages, show the distributions of water quality parameters in near-surface water for August 25-27, 1976; January 15, 1977; March 24, 1977; and July 23, 1977.

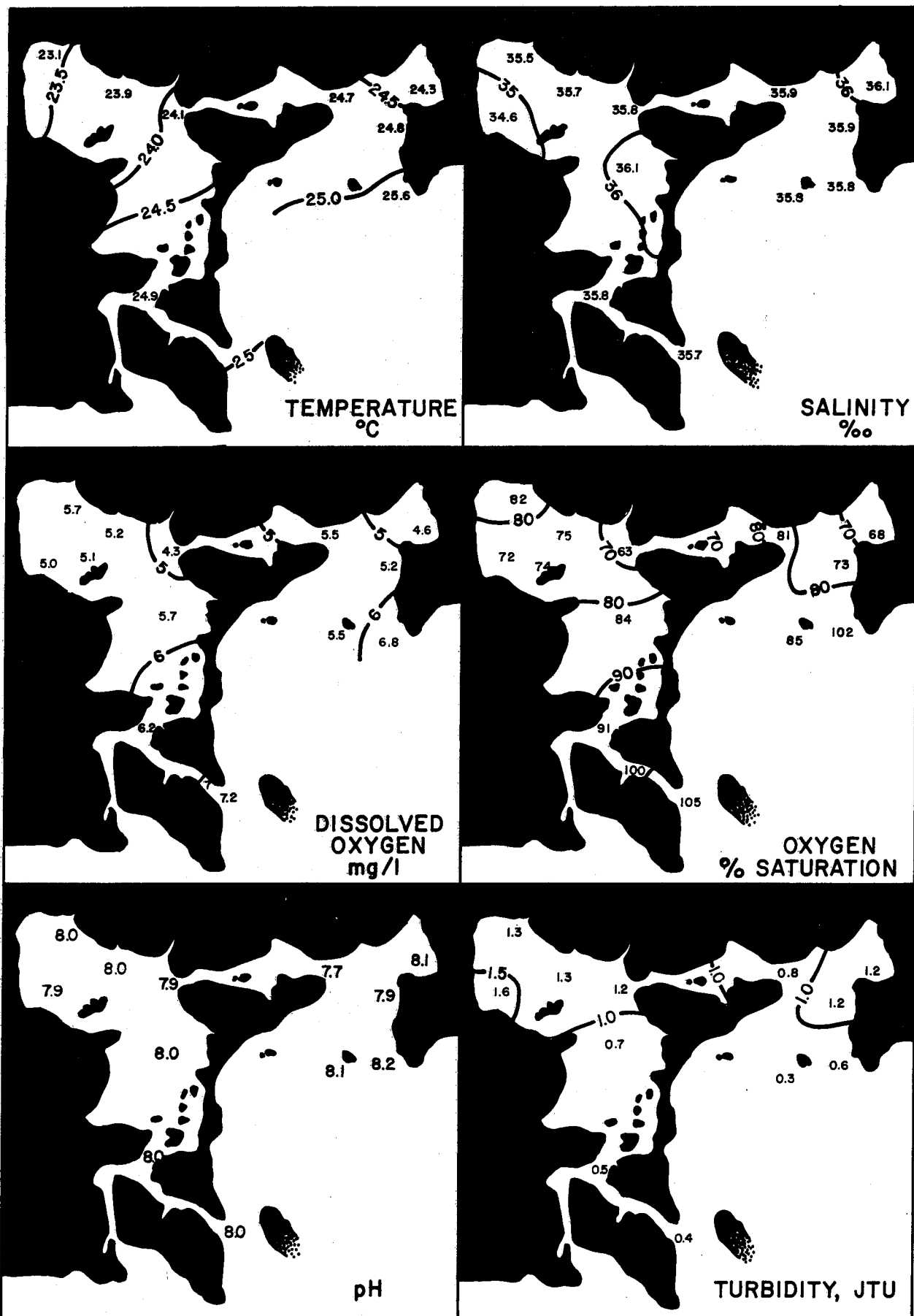
# WATER QUALITY DISTRIBUTIONS

AUGUST, 1976

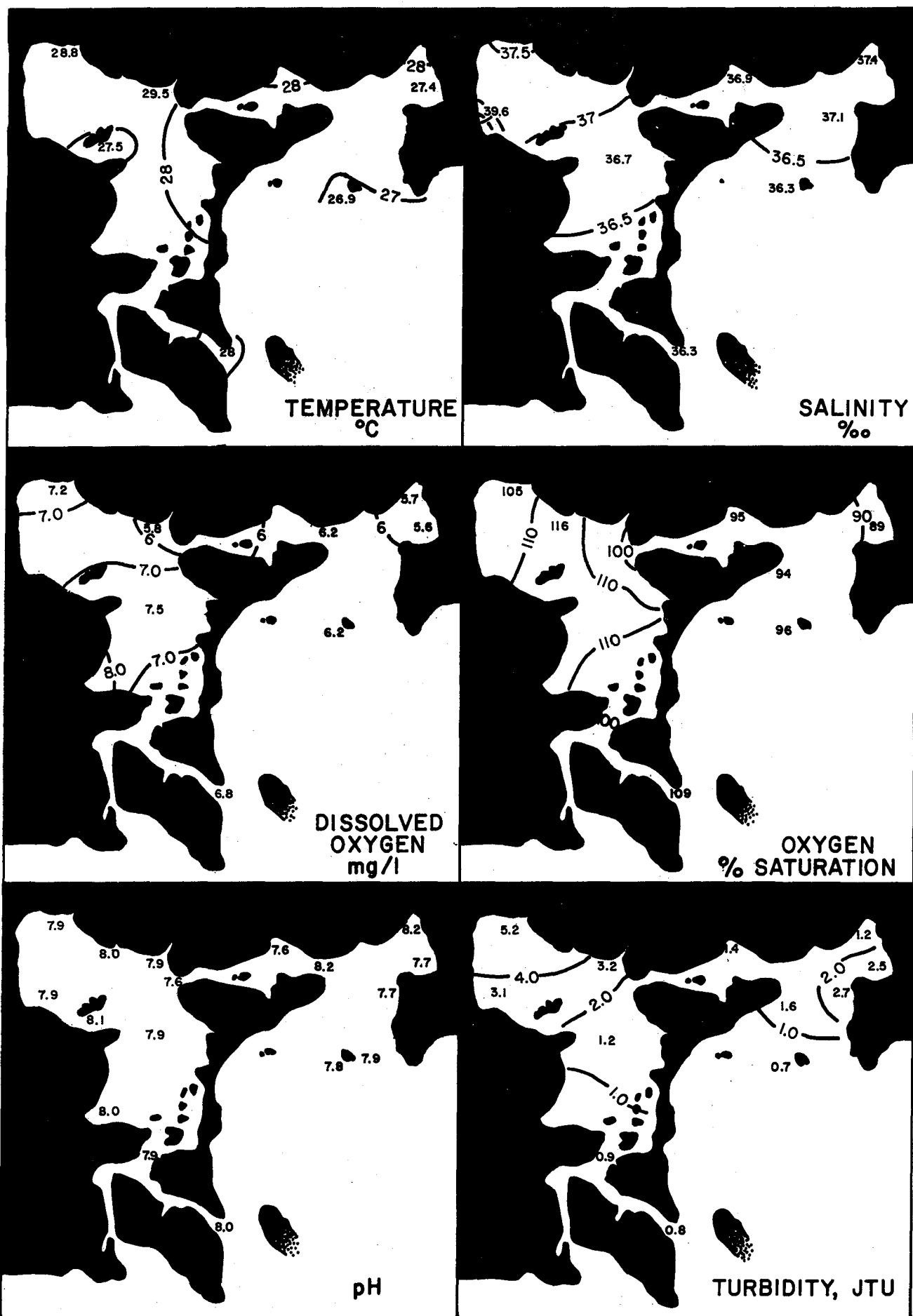




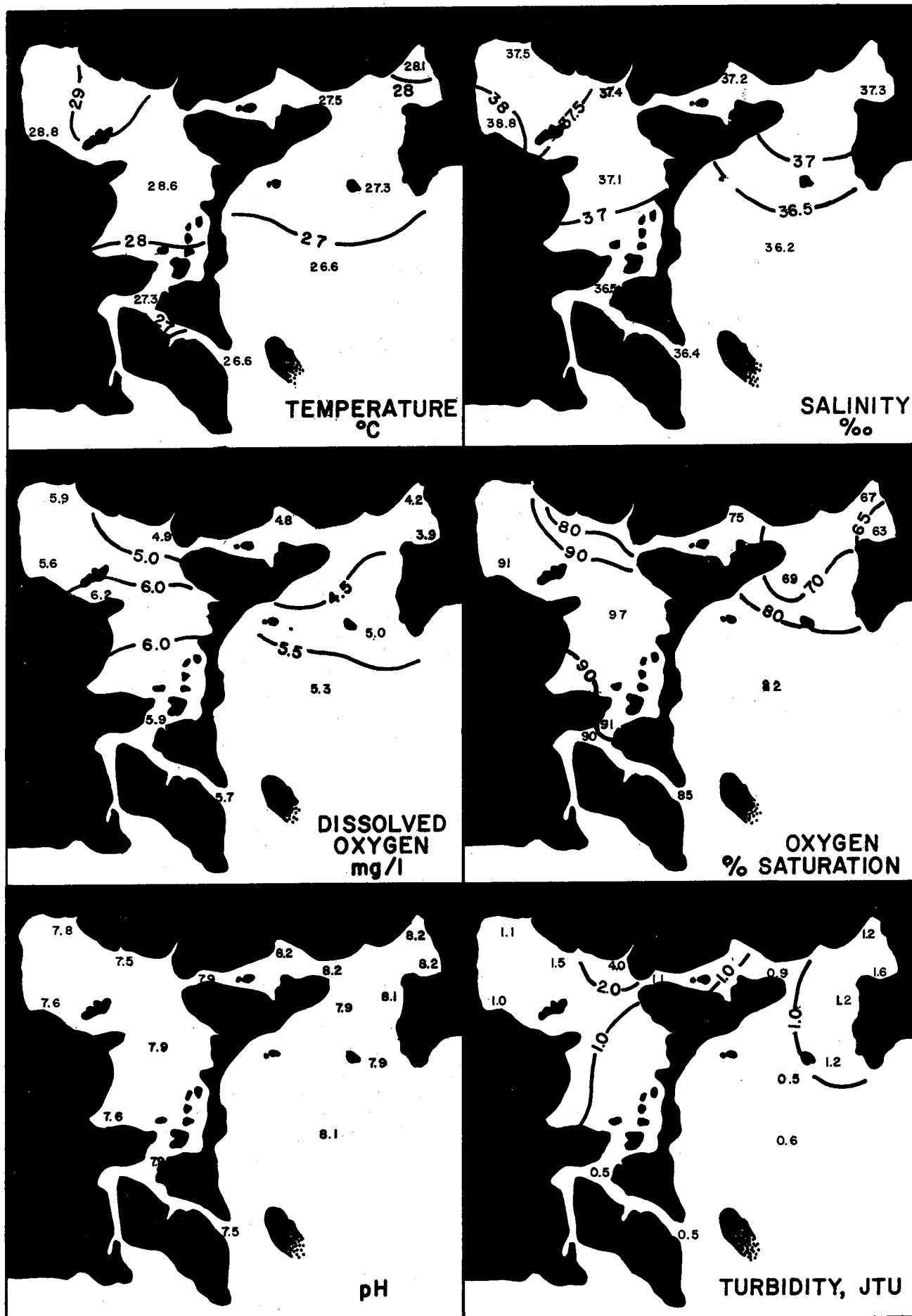
# WATER QUALITY DISTRIBUTIONS JANUARY, 1977













and March. The low concentrations are affected by a combination of high net production of organic matter, light weather and poor mixing and an influx decomposed organic material from pollution sources and runoff. Most of the low values are from near-bottom backwaters where circulation is high. Low oxygen concentrations close to the bed may be a limiting factor for benthic organisms if waters are completely depleted of oxygen.

Benner Bay is subject to increased turbidity caused by sediment influx of storm runoff. By contrast high turbidity of the inner lagoon is caused partly by plankton blooms particularly following runoff from Turpentine Run. For another part blooms are created by discharge of sewage when the treatment plant is broken down.

Turbidity is an important stress on the lagoon and bay environment. Sunlight must be able to penetrate coastal waters so as to foster the growth of both the rooted plants, such as turtle grass. Increased turbidity from the addition of suspended matter to the water reduces light penetration and has a negative effect on plant growth.

Turbidity has most likely excluded turtle grass from inner reaches within the last eight years. By limiting light penetration it has restricted the grass to shoals and lighted areas of seaward reaches.

The high turbidity values recorded in the lagoon during 1976-1977 are part of a long-term trend of increasing maximal turbidity which began in 1974. On the other hand, in Benner Bay, turbidity has improved slightly since 1975.

Turbidity distributions in the lagoon form a gradient that decreases seaward from the lagoon and bay head to Jersey Bay. The most marked change takes place in the central lagoon and in the Benner Bay entrance during summer. This change reflects the source of turbidity, sewage as well as suspended plankton and their seaward dispersal and dilution by less turbid water of Jersey Bay. Locally high turbidity develops during windy periods when waves resuspend muddy sediments from shoals. A similar local increase is produced by boat wakes.

The pH (hydrogen ion concentration) varies within narrow limits throughout most of the lagoon. The annual range is normally 7.7 to 8.4 but a slightly greater range occurs locally in ponds. This indicates the lagoon and bay are well buffered with seawater in its neutral or slightly hypersaline state. The pH of the bay system is relatively stable and does not represent a stress or act as a limiting factor for organisms.

Dissolved phosphorus is markedly higher in the Mangrove Lagoon than in Jersey Bay. Concentrations are more than 100 times greater. High values were recorded from the mouth of Turpentine Run in January 1977, from backwaters of Middle Island, and the lagoon head in September 1976. These high concentrations together with diminished oxygen content give evidence for eutrophication (over fertilization). Relatively large differences between dissolved and total phosphorous indicate the phosphorous is associated with particulate material, mainly phytoplankton. The phosphorous is released by death and

decay of phytoplankton which partly thrive on sewage. For another part they are nourished by decomposition of mangrove detritus or by influx of phosphorous in runoff. The phosphorous is particularly excessive when combined with nitrogenous wastes and triggers phytoplankton blooms in poorly circulating lagoon waters

# WATER QUALITY TRENDS

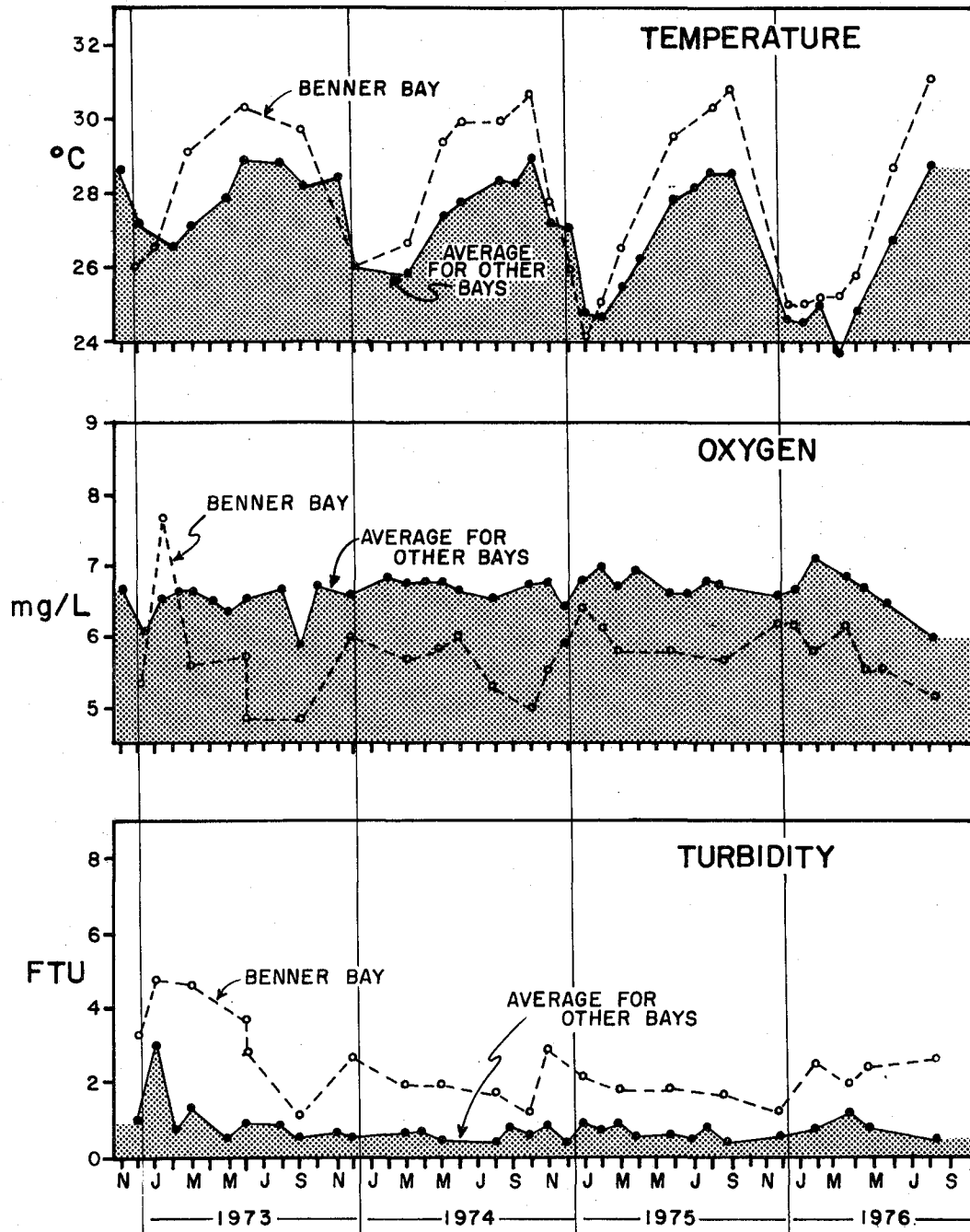


Figure 28. Monthly water quality trends at Benner Bay compared with average for south coast bays, 1973-1976.

Productivity. Rates of gross community photosynthesis (primary production) and total community respiration in the water were determined from light-dark bottles and from the diurnal oxygen curves using the graphical method of Odum and Hoskins (1958). Table 8 summarizes values of production at key stations in the lagoon and compares data derived from 1970 oxygen curves with those obtained in the present study, 1976.

One of the by-products of the diurnal curve analyses is the gas transfer constant (K) which indicates the rate of oxygen diffusion into or out of lagoon water per unit saturation deficit gradient. This diffusion constant also provides an estimate of the maximum excess of respiration over production that is permissible for the lagoon without conditions becoming anaerobic. For example, if 10 percent saturation is lethal for fish, a fish kill may be expected when the  $R_1$  values (shown in the last column of Table 8) exceed the measured R values. On August 25 in the upper lagoon at Stations 27A, 27B,  $R_1$  values were very close to R values, indicating that the lagoon had almost reached its capacity to accept organic pollution. It was close to a metabolic threshold beyond which the system would break down.

Free water gross production shown in Table 8 ranges from 8.0 - 43.3 gm/m<sup>2</sup>/day. The highest rate is at the lagoon head (Station 27B), whereas the lowest rate is in Bovoni Passage (Station 9). Gross production exceeds respiration at all stations measured and there is a substantial net production of from 2.1 - 15.6 gm/m<sup>2</sup>/day. Net production is generally two times greater in 1976 than in 1970. This is caused by more rapid metabolism, both gross production and respiration, rather than an increase in

Table 8. Values for range of oxygen saturation gross production (Pg), community respiration (R), and net production (Pn). K is the diffusion constant at 0% saturation. R<sub>1</sub> is the maximum respiration necessary to produce an oxygen saturation of 10 percent.

| Location                               | Date             | Oxygen Saturation % | Light-Dark Bottle Method<br>gms/m <sup>2</sup> /day |     |     | Free-Water Curve Method<br>gms/m <sup>2</sup> /day |      |      | K   |
|----------------------------------------|------------------|---------------------|-----------------------------------------------------|-----|-----|----------------------------------------------------|------|------|-----|
|                                        |                  |                     | Pg                                                  | R   | Pn  | Pg                                                 | R    | Pn   |     |
| Cas Entrance Reach #1                  | Aug. 18-19, 1976 | 86-120              | 1.5                                                 | 1.1 | 1.5 | 10.6                                               | 8.0  | 2.6  | 2.1 |
| Benner Bay #7                          | Mar. 21-22, 1970 | 94-124              | ---                                                 | --- | --- | 10.6                                               | 8.5  | 2.1  | 2.3 |
| Benner Bay #7                          | Aug. 25, 1976    | 74-123              | 7.4                                                 | 3.6 | 3.8 | 14.9                                               | 9.6  | 5.3  | 1.7 |
| Bovoni Passage #9                      | Mar. 21-22, 1970 | 85-114              | ---                                                 | --- | --- | 7.1                                                | 4.2  | 2.9  | 0.2 |
| Bovoni Passage #9                      | Aug. 18-19, 1976 | 67-115              | 8.3                                                 | 5.3 | 3.0 | 13.7                                               | 8.7  | 5.0  | 0.2 |
| Mangrove Lagoon #10<br>(Inner Reaches) | Mar. 21-22, 1970 | 68-124              | ---                                                 | --- | --- | 8.0                                                | 4.4  | 3.6  | 0.3 |
| Mangrove Lagoon #10<br>(Inner Reaches) | Aug. 25, 1976    | 90-161              | 7.4                                                 | 1.4 | 6.0 | 13.9                                               | 8.8  | 5.1  | 0.9 |
| Mangrove Lagoon #27A<br>(Lagoon Head)  | Aug. 25, 1976    | 94-169              | 8.7                                                 | 3.2 | 5.5 | 15.8                                               | 5.0  | 10.8 | 1.3 |
| Mangrove Lagoon #27B<br>(Lagoon Head)  | Aug. 25, 1976    | 96-212              | 11.2                                                | 5.9 | 5.3 | 43.3                                               | 27.7 | 15.6 | 0.2 |

Table 9. Values for gross production (Pg), respiration (R), and net production (Pn) by light-dark bottle method and changes in production between August, 1976 and January, 1977.

| Location                                  | Date             | Oxygen Saturation % | Light-Dark Bottle Method<br>gms/m <sup>2</sup> /day |     |     | Changes Between August 1976 and Jan. 1977<br>gms/m <sup>2</sup> /day |      |      |
|-------------------------------------------|------------------|---------------------|-----------------------------------------------------|-----|-----|----------------------------------------------------------------------|------|------|
|                                           |                  |                     | Pg                                                  | R   | Pn  | Pg                                                                   | R    | Pn   |
| Cas Entrance Reach # 1                    | Aug. 18-19, 1976 | 86-120              | 1.5                                                 | 1.1 | 0.4 | -                                                                    | -    | -    |
| Benner Bay #7                             | Aug. 25, 1976    | 74-123              | 7.4                                                 | 3.6 | 3.8 |                                                                      |      |      |
|                                           | Jan. 16-17, 1977 | 68                  | 2.6                                                 | 0.2 | 2.4 | -4.8                                                                 | -3.4 | -1.4 |
| Bovoni Passage #9                         | Aug. 18-19, 1976 | 67-115              | 8.3                                                 | 5.3 | 3.0 | -                                                                    | -    | -    |
| Mangrove Lagoon #10<br>(Inner Reaches)    | Aug. 25, 1976    | 90-161              | 7.4                                                 | 1.4 | 6.0 | -                                                                    | -    | -    |
| Mangrove Lagoon #27A<br>(Lagoon Head)     | Aug. 25, 1976    | 94-169              | 8.7                                                 | 3.2 | 5.5 |                                                                      |      |      |
|                                           | Jan. 16-17, 1977 | 82                  | 0.4                                                 | 0.2 | 0.2 | -8.3                                                                 | -3.0 | -5.3 |
| Mangrove Lagoon #27B<br>(Lagoon Head)     | Aug. 25, 1976    | 96-212              | 11.2                                                | 5.9 | 5.3 |                                                                      |      |      |
|                                           | Jan. 16-17, 1977 | 72                  | 1.9                                                 | 1.4 | 0.5 | -9.3                                                                 | -4.5 | -4.8 |
| Mangrove Lagoon #10A<br>(Central Reaches) | Aug. 25, 1976    | 70                  | 4.6                                                 | 3.2 | 1.4 |                                                                      |      |      |
|                                           | Jan. 16-17, 1977 | 84                  | 2.6                                                 | 0.2 | 2.4 | -2.0                                                                 | -3.0 | +1.1 |

respiration alone. The higher net production in 1976 indicates there is more organic matter being produced in the lagoon than is consumed. Thus, a substantially greater amount of organic matter is available for storage in the sediments. Despite import of sewage and mangrove detritus, respiration does not exceed photosynthesis; instead, the sewage fertilizes the lagoon and stimulates greater production.

Rates of gross production and respiration determined from light-dark bottles are summarized in Table 9. Gross production in the bottles generally makes up more than 50 percent of the over-all free water production except at Station 27B. Metabolism in August 1976 was higher at all stations than in January. This reflects diminished growth of phytoplankton in January 1977, a time of low light intensity and reduced nutrient supply. During August metabolism is much greater at stations near inner reaches than near the entrance. This also reflects greater production of phytoplankton in inner parts despite the high turbidity.

Biologic activity is stepped up by nutrients released from secondary sewage treatment. Such nutrients increase the growth rate of phytoplankton leading to blooms which render the water turbid. They create large diurnal changes in oxygen content ranging from supersaturation in the surface near mid-day to complete depletion near the bottom in early morning. Oxygen consumption is further reduced by oxidation of untreated boat sewage and by petroleum wastes that contain large amounts of reduced carbon.

Bottom Sediments. The Mangrove Lagoon is floored with a variety of different sediment types ranging from fine mud to coarse sand. Figure 29 indicates the distribution of different types which were determined by macroscopic examination. The inner lagoon floor is predominantly mud whereas seaward reaches are predominantly sand. Between these two main types, or end members, are mixtures of mud and sand. Halimeda, which grows on the lagoon floor, is the chief sand constituent of the mixed sediment while quartz and feldspar are important in seaward reaches.

Sediments from Benner Bay exhibit similar types, but the distribution patterns differ. Medium sand covers the entrance shoals while muddy sand predominates the channel floor. Although the channel sediments are suitable for dredging, they contain too much clay and silt for use as aggregate without special processing. They are, however, suitable for fill where 20-30 percent fines can be tolerated.

Mud from the inner lagoon floor contains the highest organic matter, up to 14 percent by loss-on-ignition (Figure 30 ). Some of the organic material is a by-product of pollution, either sewage pollutants absorbed on fine-grained particles or dead organisms thriving on nutrient-rich pollutants. Some of the material is undoubtedly detritus derived primarily from leaf fall in adjacent mangroves.

The distribution of carbonate sediment determined by HCl digestion is given in Figure 31. Most of the carbonate in lagoon sediments reflects the percentage of sand contributed by Halimeda, whereas low carbonate reflects high proportions of terrigenous particles eroded from headlands.

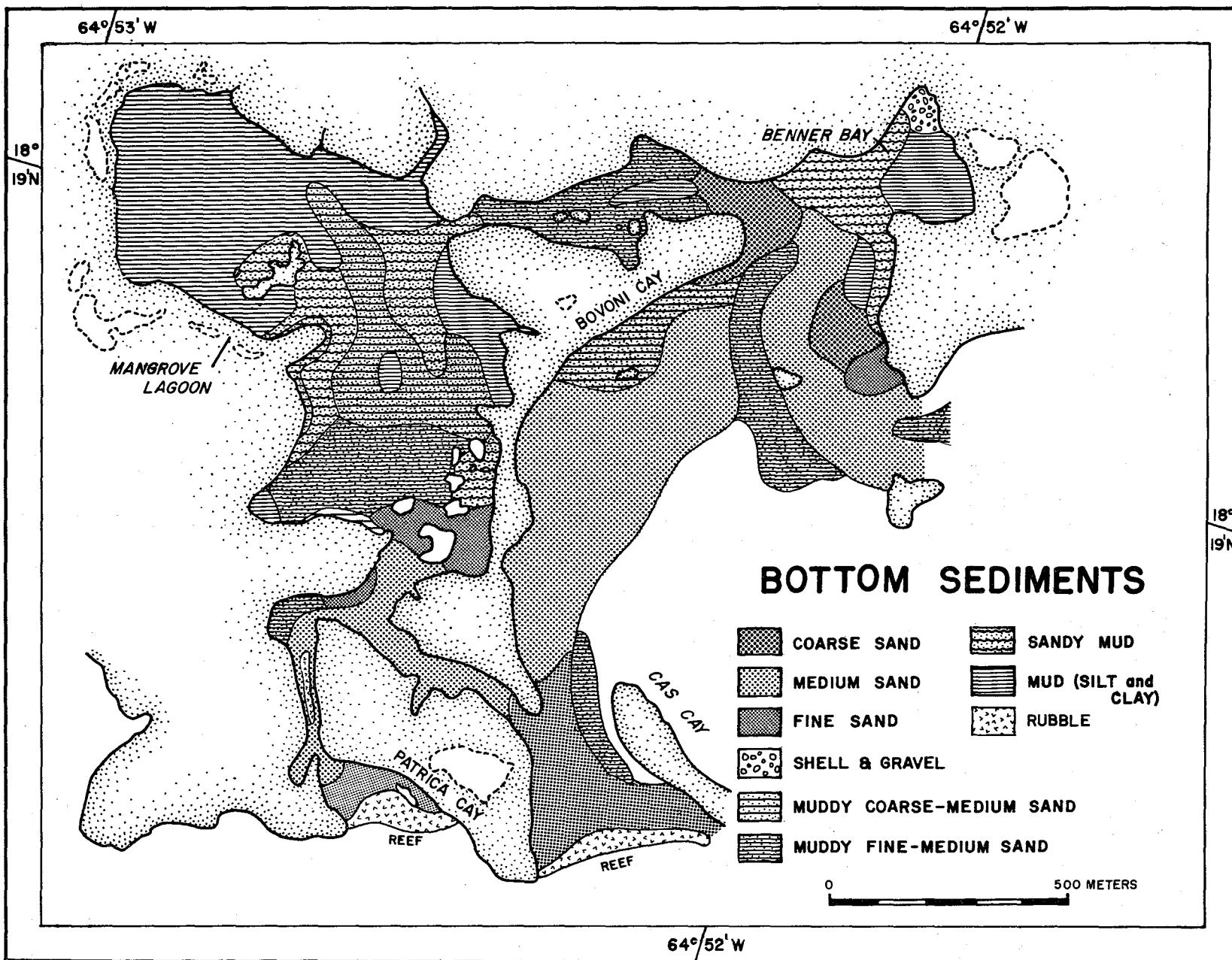


Figure 29. Distribution of bottom sediment types.

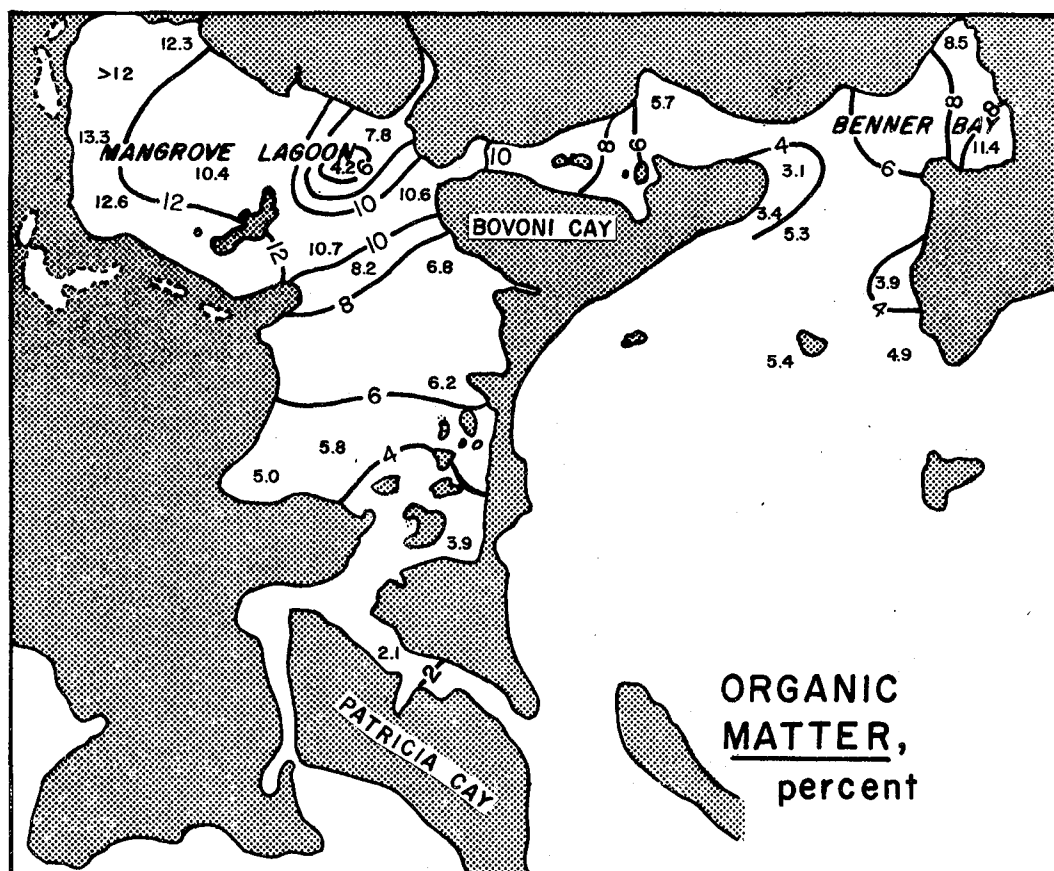


Figure 30. Distribution of organic matter in sediments.

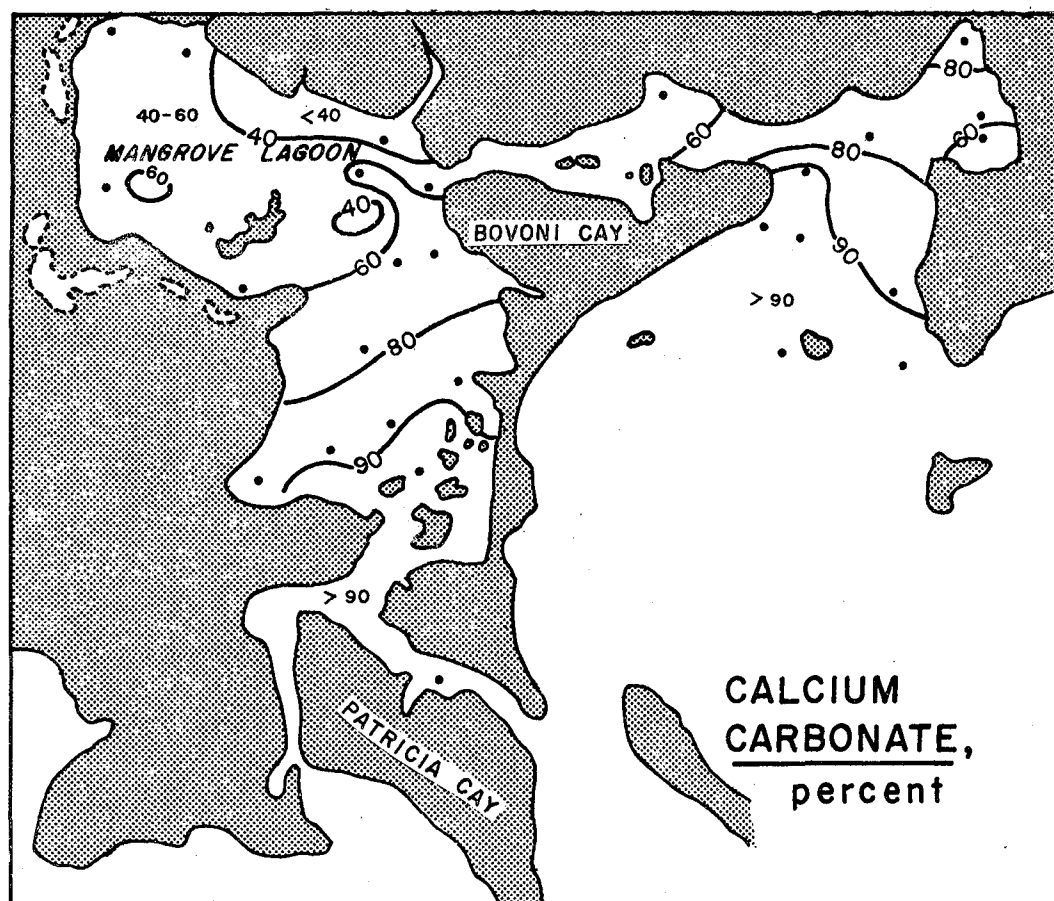


Figure 31. Distribution of calcium carbonate in sediments.

## Sediment Chemistry

In an area receiving pollutants the bottom sediments provide an index to the source and extent of pollution. When pollutants enter a coastal environment they disperse into different parts of the environment according to their chemical reactivities and biological availabilities. Often bottom sediments concentrate pollutants many orders of magnitude above levels found in solution. They negate the old adage that "dilution is the solution to pollution". Since sediments are less transient than water which moves with the tide and wind, they indicate the location and intensity of pollution in relation to its source.

The methods used to determine trace metals and nutrients are given in Appendix I. Samples mainly consist of bulk surface sediment. A few samples were taken from cores to determine the depth distribution of contaminants.

The distribution of trace metals and various organic constituents is shown in Figure 32. Data are tabulated in Table 10 and station locations are given in Figure 3.

The metals, copper, lead and zinc are higher than normal in sediments from Benner Bay, Bovoni Passage, at the mouth of Turpentine Run and 40 to 100 meters lagoonward (east) from the municipal dump. They are concentrated mainly in fine-grained muddy sediments close to pollution sources, the municipal dump, entering streams and marinas. Such metals are commonly used in marine bottom paint and sacrificial anodes. With the exception of core J from the lagoon head, these constituents are higher in surface sediments than at depth in the sediments. This indicates the lagoon and bay are receiving greater amounts of copper and zinc contaminants than in the recent

past. However, most of the concentrations are restricted to innermost parts of the bay and lagoon and have not spread throughout the lagoon or seaward into Jersey Bay.

Of the other metals examined, cadmium and mercury, concentrations are normal for most of the area except at Station I in Benner Bay where mercury is unusually high. All metal concentrations except mercury were exceptionally high in ground water in the alluvial substrate. High salinity of the ground water greater than 150 ppt. suggests the metals are concentrated in the flats by high evaporation of capillary water from the surface of the flats.

Oil and grease concentrations are highest lagoonward from the municipal dump (100 m). Substantial concentrations were also found at the entrance to Turpentine Run and in Benner Bay where they are most likely a product of bilge wastes and local oil spillage.

Total phosphorus, nitrogen and chemical oxygen demand are unexpectedly high in the inner parts of the Mangrove Lagoon and Benner Bay than elsewhere. This reflects a relatively high nutrient input or regeneration of organic pollutants in these zones.

The results indicate that sediments in the proposed dredged channel of Benner Bay contain moderate amounts of lead and copper that could present a disposal problem. The Environmental Protection Agency defines regulations and criteria for ocean dumping (Federal Register, Vol. 42, No. 7 - Tuesday, January 11, 1977). In section 227.6, e. is given the "Conditions" which must be met in the absence of bio-assay results for disposal. Not all potentially toxic constituents in the area have been analyzed.

Table 10. Concentration of chemical constituents in sediments from the Mangrove Lagoon and Benner Bay.

| Sample No.       | % TS | % VS | PPM TP | PPM TKN | PPM O&G | % COD | PPM Cd | PPM Cu | PPM Zn | PPM Pb | PPM Hg |
|------------------|------|------|--------|---------|---------|-------|--------|--------|--------|--------|--------|
| 13&400           | 48.5 | 9.40 | 130    | 2600    | 920     | 13.0  | 1.7    | 11     | 19     | 25.    | <.002  |
| 27B              | 30.3 | 11.7 | 180    | 4400    | 380     | 9.2   | 1.5    | 30     | 50     | 33     | <.002  |
| 10A              | 30.5 | 13.0 | 89     | 3900    | 1200    | 6.3   | 2.3    | 12     | 22     | 36     | <.002  |
| K                | 47.1 | 10.7 | 2      | 2600    | 1300    | 6.5   | 1.1    | 38     | 79     | 59     | <.002  |
| L                | 55.5 | 9.81 | 2      | 1200    | 740     | 6.6   | 1.1    | 40     | 65     | 45     | 0.060  |
| G                | 66.5 | 5.58 | 240    | 1000    | 580     | 2.1   | 2.0    | 47     | 44     | 30     | <.002  |
| 67               | 55.7 | 7.94 | 180    | 1200    | 240     | 1.1   | 2.0    | 31     | 31     | 27     | <.002  |
| Tutu*            | 65.0 | 6.63 | 5.8    | 2000    | 330     | 6.4   | 0.14   | 25     | 29     | 10     | 0.034  |
| 47               | 89.5 | 8.39 | 2      | 1700    | 290     | —     | 0.46   | 17     | 79     | 53     | 0.078  |
| 48               | 92.8 | 9.44 | 2      | 1000    | 260     | 3.4   | 0.65   | 140    | 150    | 54     | 0.020  |
| 49               | 59.9 | 14.3 | 17     | 2300    | 3600    | 7.4   | 1.8    | 67     | 121    | 110    | 0.033  |
| 20               | 57.1 | 4.87 | 84     | 280     | 350     | 2.1   | 1.7    | 7.7    | 7.4    | 18     | 0.0002 |
| R*               | 55.3 | 7.57 | 150    | 1400    | 450     | 1.9   | 2.0    | 25.    | 33     | 45     | 0.056  |
| 48 GW**          | —    | —    | —      | —       | —       | —     | 0.19   | 0.20   | 0.12   | 0.91   | ND     |
| A2-A3, 0-2 cm.   | 60.5 | 5.27 | 44     | 830     | 270     | 2.7   | 2.6    | 17     | 10     | 2.0    | 0.028  |
| A2-A3, 43-45 m   | 60.1 | 5.08 | 170    | 370     | 92      | 2.1   | 2.5    | 7.6    | 5.5    | 9.6    | 0.007  |
| Core J, 0-3 cm   | 39.0 | 12.3 | 320    | 3800    | 590     | 13    | 1.9    | 35     | 62     | 20     | 0.010  |
| Core J, 30-33 cm | 43.7 | 12.4 | 71     | 2700    | 130     | 14    | 1.2    | 40     | 53     | 15     | 0.005  |
| Core I, 0-3 cm   | 48.2 | 11.4 | 80     | 2200    | 890     | 15    | 1.9    | 120    | 110    | 24     | 0.23   |
| Core I, 30-33 cm | 49.3 | 9.47 | 76     | 1500    | 170     | 12    | 2.7    | 15     | 19     | 11     | 0.020  |

\* Pesticides all negative

\*\* Ground water 50cm below surface

# CHEMICAL CONSTITUENTS IN SEDIMENTS

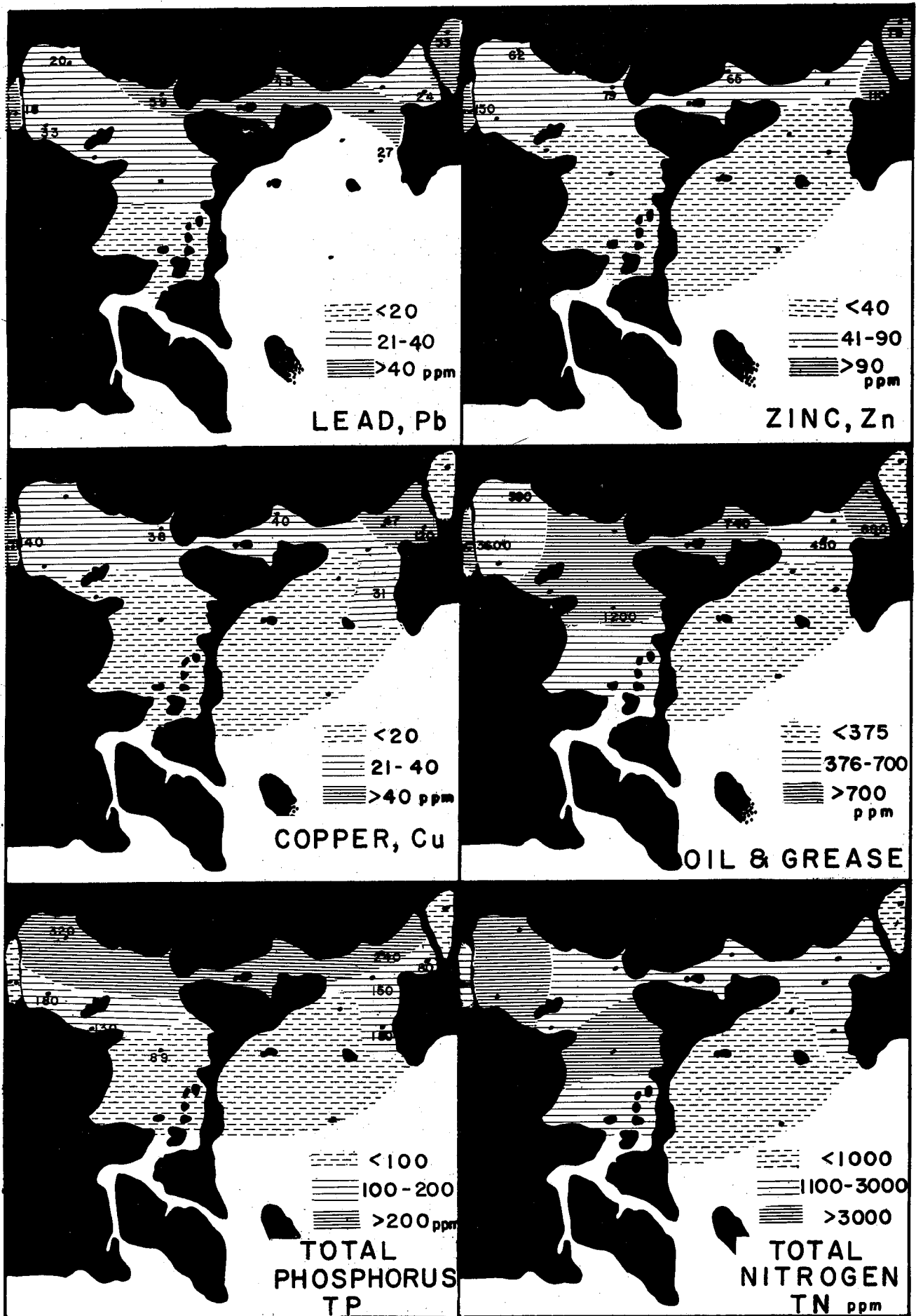


Figure 32. Distribution of chemical constituents in surface sediments.

## 9. Biological Conditions

Mangrove Studies. Comparison of mangrove distributions deduced from a chart dated 1851 (Figure 11) with those recorded in the 1947 aerial photo (Figure 7) show little change. The basic distributions were essentially stable for 96 years. Small changes are evident, however, in recent years. The 1954 aerial photographs indicate establishment of trees at Middle Island (point a, Figure 39B) while the 1965 photographs show that trees extend the shoreline seaward from Bovoni Cay (point b, Figure 39C). Additionally, manglars were established on submerged shoals in Jersey Bay (point c, Figure 39C) and these have continued to expand until the present day (Figures 6 and 40).

Patricia Cay. This cay, located in the southern part of the Mangrove Lagoon (Figure 8), consists of an elongated structure of coral shingle and sand about 35-40 meters wide. Behind this ridge mangroves have grown into the lagoon for approximately 200 meters. A headland, Patrick Point, "anchors" the east end of the ridge.

The south shore is colonized by mangroves of two species: Rhizophora mangle (red mangrove) and Laguncularia racemosa (white mangrove). The slope of the beach face allows only a fringe of mangroves two or three trees wide to develop. Typical beach scrub develops on the ridge. Along the south shore Rhizophora does best toward the eastern part of the cay where the sand has a higher silt content whereas Laguncularia is the dominant tree at the fringe toward the inlet at the west end. Toward this side coarse sands prevail and Rhizophora does not seem to be very successful in this

substrate. Where Rhizophora occurs in the outer part of the fringe, Laguncularia follows behind growing at a slight elevation on the sloping beach face. Figure 33A summarizes elevation data.

Behind the ridge is a large salt pond with relatively high salinity. The mean surface salinity measured (August, 1977) was 50 ppt, while the salinity of the soil water underlying the pond was considerably higher, ranging between 80 ppt and 90 ppt. Dead and/or dying mangrove trees, mainly Avicennia, the black mangrove, are found here. This species is the dominant species fringing the hypersaline pond.

Behind the black mangroves and toward the Mangrove Lagoon a wide fringe of red mangroves occurs. This fringe is as wide as 200 meters in places. An interesting characteristic of these mangroves is their "scrubbiness"; vegetation heights are less than two meters. Macnae (1968) observed that scrubbiness increases with higher soil salinities and Cintron and Lugo (in press) demonstrated for the mangrove forests studied that tree height decreased directly with increased soil salinity. However, surprisingly, waters inundating these mangroves which are submerged by most tides have relatively low salinity (36 ppt) as does the underlying soil water (38 ppt). Other factors such as flushing and nutrient inputs affect structural development and must be related to the stunted character of the vegetation. These are discussed later. The color of the leaves of these stunted mangroves was slightly more yellow than the tall mangroves elsewhere in the bay: 5 GY 4/6 for the low mangroves and 5 GY 5/4 for tall mangroves. Colors ranging from 2.5 GY 5/4,

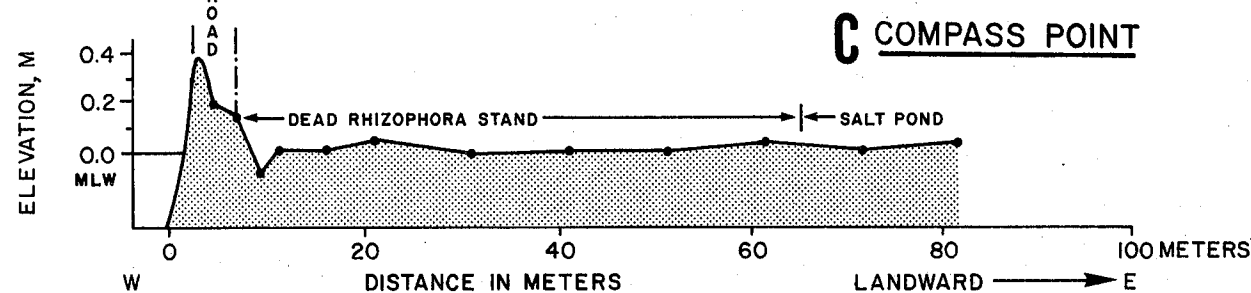
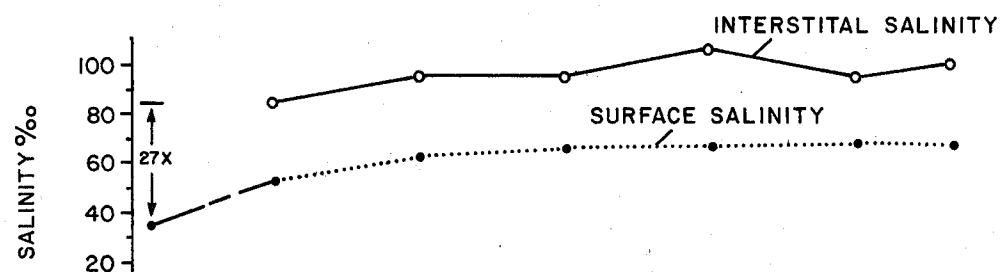
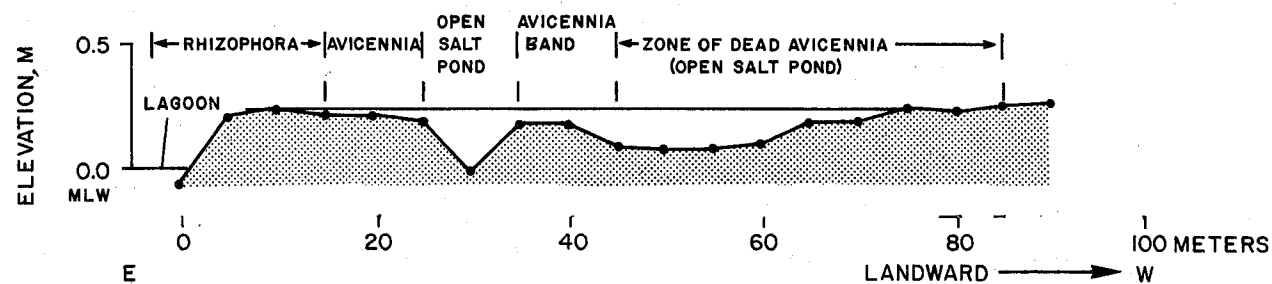
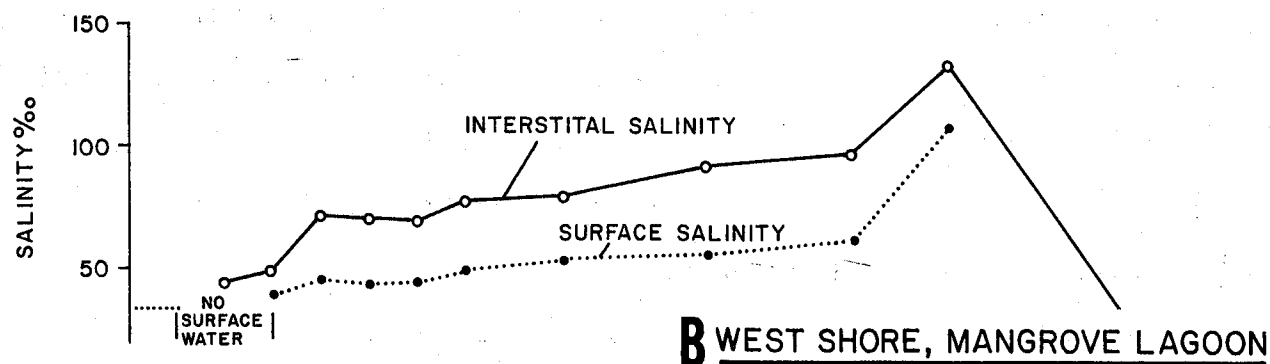
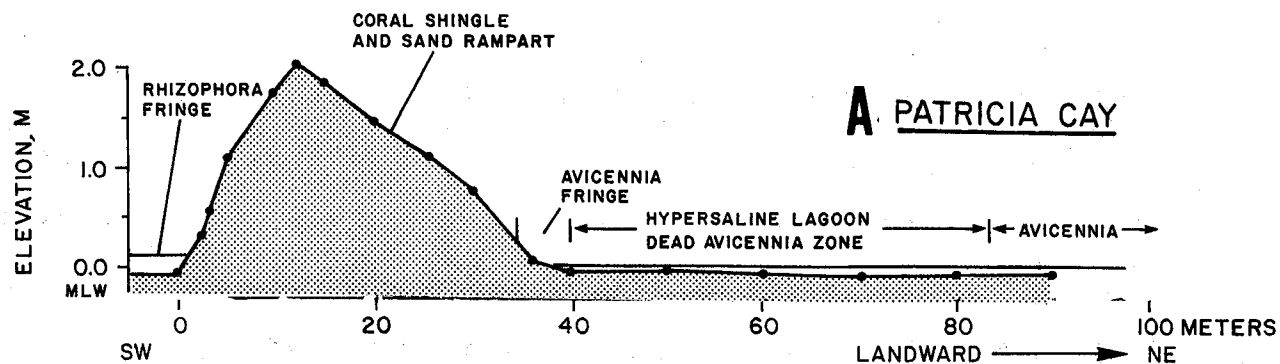


Figure 33. Elevation and salinity profiles across mangrove zones on A. Patricia Cay; B. West shore of lagoon; C. Compass Point.

5/5 were also observed in the low mangroves. The red mangroves at the lagoonward edge are slightly taller, about two meters, whereas those behind are only 1.50 to 1.75 meters tall.

Bovoni Cay. This is an arcuate cay or barrier island almost 1.2 km long. A sand ridge of lesser elevation than the ridge at Patricia Cay separates Jersey Bay from the Mangrove Lagoon. Mangrove growth behind this ridge is not as extensive as in Patricia Cay except at the southern tip.

Mangroves along Jersey bay are mostly reds of large size (7 meters); white mangroves grow behind these in the sandy ridge. The fringe is only a few meters wide (5-8m). Beach scrub vegetation grows in the portions not wetted by the tides. In low areas of the ridge, i.e., in the trough between what seems to be two ridges, black mangroves were observed. A forest of low reds extends toward the lagoon. As in Patricia Cay these reds are overwashed, permanently flooded except by unusual tides.

West Shore of Inner Lagoon. The mangroves along the west shore of the mangrove lagoon, in contrast to most of those in the southern lagoon, are of large size with a canopy height of  $\pm$  7 meters. The fringe varies in width between 80 m and 200 meters. They occur in what seems to be a double band separated by shallow ponds or inner lagoons. Salterns, or high tide mud flats, are found behind the fringe as in other xeric mangrove areas (Citron, Lugo, in press).

In a transect made west of the sewage treatment plant (Fig. 33B) the following zonation was observed: (1) a band of red mangroves

(14 meters wide at this site) (2) a band of black mangroves (10 m in width), the landward portion of these trees (Figure 23C) is partially defoliated dead or dying (3) a shallow depression, flooded, and (4) a band of black mangroves extending to 30 meters. The trees at the landward edge from 45 to 90 m were all dead (Figure 37) (5) a wide and high mud flat.

Soil and surface salinities at this transect are shown in Table II, Figure 33B. As can be observed the lowest surface and interstitial salinities, 36.6 ppt and 40.0 ppt, respectively, are found in the red mangrove band. Higher values are found in the black mangrove band where the mean surface was 48.8 ppt and the mean interstitial water was 61.4 ppt. The salt pond had a mean surface salinity of 56.8 ppt; the underlying interstitial water salinity was 93.2 ppt. The landward black mangrove forest, which is mostly dead, had a surface salinity of 56.8 ppt and an interstitial salinity of 93.2 ppt. The salt flat had interstitial and soil salinities of 100-135 ppt. A pit dug to a depth of 30 cm just above the reach of the high water mark yielded water of 20 ppt salinity. The top 10 cm of this pit was composed of a yellow clay which overlies gray mangrove mud.

To the west of the transect area an elevated road bed is found and, adjacent to this, road fill was deposited on the mud flat. This area is above tide level and fresh water accumulates here. The fill material is fairly impermeable, and pools of fresh water rest here. Again a pit in this area showed 20 cm of yellow clay with the fill material resting on gray mud. The underlying soil water had a salinity of 36 ppt. Because of the presence of

fresh water, grasses grow adjacent to the rear of the mangrove forest. This anomaly is due to the alteration of the mud flat topography.

Compass Point and Salt Pond. This area is of particular interest because it shows that mangroves can be killed not only directly by cutting but also by the indirect effects of changes in drainage patterns leading to stagnations and salt accumulation. The aerial photography of 1947 shows this area as a shallow embayment with mangroves growing as a wide fringe, probably 70 meters wide, across the mouth. In the 1954 photography a salt flat is observed behind the mangrove fringe, and this salt flat is more prominent in the 1965 photograph. A wide zone of mangrove seems to have been removed between 1954 and 1965. Some mangrove growth is observed along the edge of the embayment in all of these photographs. Sometime between 1965 and 1971 a road was built across the mouth of the embayment. Most of the salt pond and a portion of the mangrove fringe was sealed off by the solid fill road from Benner Bay. The forest, which consisted of tall red mangroves, appears dead or dying in the 1972 photograph. See figures 23A and 23B.

This area was visited in August 1977, a time when the surface water inside the embayment (pond) averaged 65 ppt salinity. The interstitial salinity, however, was considerably higher, between 95 and 106 ppt. Tree height was 15 meters and mean D.B.H. was 22 cm (these measurements were made on the trees still standing). The road, except in a narrow area, impedes the drainage of the water between Benner Bay and the salt pond. No recovery of

the mangroves was noted. Some red mangrove seedlings were observed within the embayment but these showed extensive salt damage and will probably not survive for long. Within the salt pond embayment a clump of dwarfed black mangroves was also observed (ht. 1.5 cm). The interstitial salinity there was about 89 ppt and the surface salinity was 56 ppt. On the Benner Bay (west) side of the road, near the northern corner of the mud flat, the surface salinities were about 54 ppt and the interstitial salinities were about 75 ppt. These values are close to what they are naturally in this type of environment. The bay salinity here was 36 ppt. Figure 33C and Table 11 summarize salinity and elevation data.

In 1947, when mangroves were extensively cut for wood, aerial photos reveal the stands covered an area of 134,263 sq. meters throughout the lagoon and bay. In 1972, the mangroves covered an area of 199,706 sq. meters an apparent increase of 67 percent. However, about 15 percent of the 1972 mangroves were dead or dying. Many stands were buried by landfill used to construct shorefront marinas, docks and a racetrack (Figures 34, 38). Others died out around margins of salt ponds where tidal drainage has been restricted by road fill, sedimentation and uncontrolled waste disposal (Figure 35).

Table 11. Surface and Interstitial Salinities (ppt) for Mangrove Forests, Salterns and Hypersaline Lagoons  
1 Standard Error of the Mean Shown (s.e)

| <u>Location</u>                          | <u>SALINITY</u> |      |                     |      |
|------------------------------------------|-----------------|------|---------------------|------|
|                                          | <u>Surface</u>  |      | <u>Interstitial</u> |      |
|                                          | $\bar{x}$       | s.e  | $\bar{x}$           | s.e  |
| <u>Benner Bay</u>                        |                 |      |                     |      |
| Compass point<br><u>Rhizophora</u> stand | 55.8            | 0.20 | 90.2                | 1.56 |
| Standing water<br>20 cm. deep            | 61.3            | 3.20 | ----                | ---- |
| North Edge of<br><u>Rhizophora</u> Stand | 51.5            | 0.89 | 98.6                | 2.23 |
| <u>Avicennia</u> Stand (dwarf)           | 55.8            | 0.20 | 88.6                | 1.17 |
| Surface drainage                         | 54.0            | ---- | ----                | ---- |
| Mean (diked area)                        | 55.7            | 1.61 | 92.5                | 1.79 |
| Salt flats<br>Compass point              | 54.0            | 1.82 | 75.4                | 1.60 |
| Surface salinity<br>Lagoon               | 35.0            | ---- | ----                | ---- |
| <u>West Shore Mangrove Lagoon</u>        |                 |      |                     |      |
| Living <u>Rhizophora</u> fringe 0-14 m   | 36.6            | 1.40 | 40.0                | 1.38 |
| Living <u>Avicennia</u> fringe 15-20 m   | 48.8            | 1.74 | 61.4                | 4.90 |
| Mean (living Mangrove)                   | 42.7            | 1.57 | 50.7                | 3.50 |
| Zone of dead <u>Avicennia</u> 50 m       | 56.8            | 2.08 | 93.2                | 1.07 |
| Saltern (Mud flats) 80 m                 | 108.7           | 8.41 | 133.3               | 1.05 |
| Rear of saltern 120 m 40 cm              | -----           | ---- | 20.0                | 0.00 |
| <u>Mangrove Lagoon</u>                   |                 |      |                     |      |
| Hypersaline lagoon<br>Patricia Cay       | 48.6            | 0.67 | 83.3                | 2.40 |
| Tall Mangroves<br>( <u>Rhizophora</u> )  | 34.0            | 0.00 | 39.0                | 0.00 |
| Low Mangroves<br>(Bovoni Cay)            | 35.8            | 0.25 | 38.0                | 0.00 |

Figure 34. Exposure of landfill along the lagoon shore at the racetrack which buried former mangrove stands. Erosion of unstabilized fill is now a local source of turbidity that degrades water quality. Black mangroves, right background, "anchor" parts of the shore.

Figure 35. Uncontrolled trash disposal along landward margin of the lagoon near the shore road at the mouth of Turpentine Run, restricts drainage in mangrove ponds causing mangroves to die. The trash and debris are a source of metal and chlorinate contamination. Dumping by boats and cruise ships also contribute much trash that accumulates in mangrove roots.

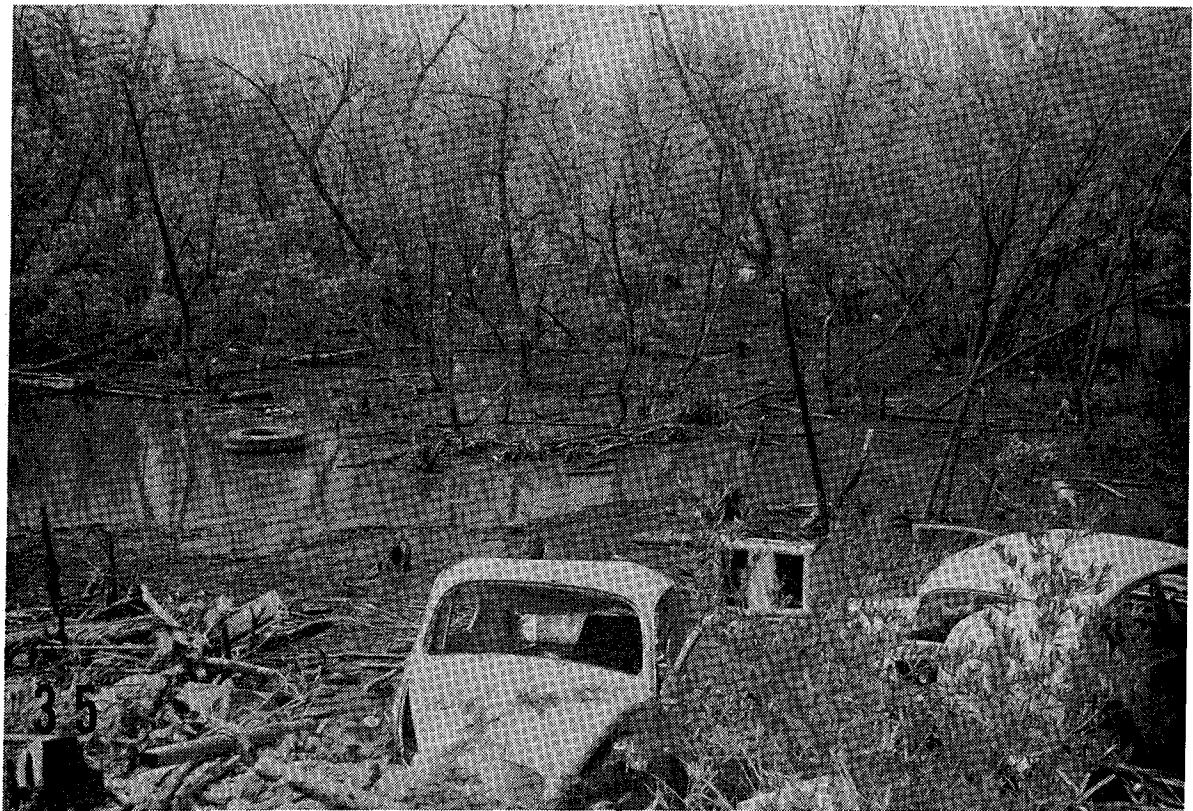
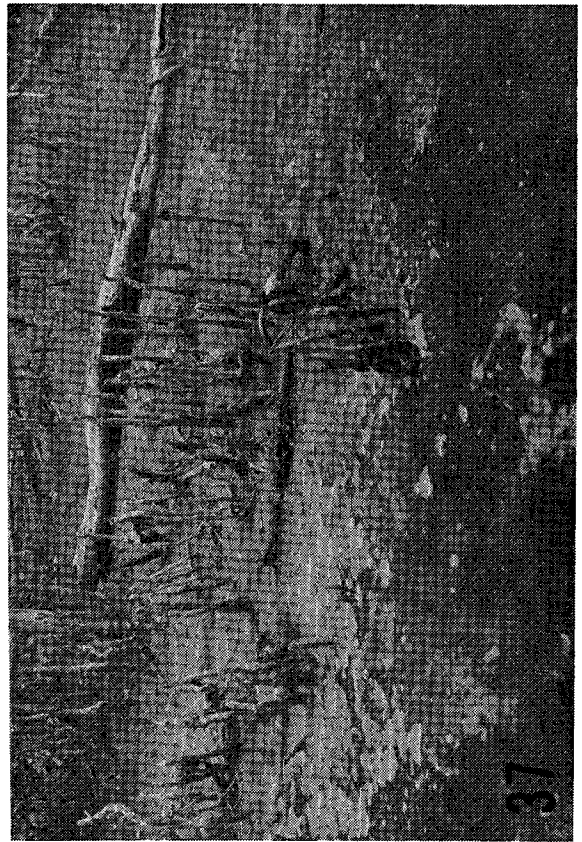
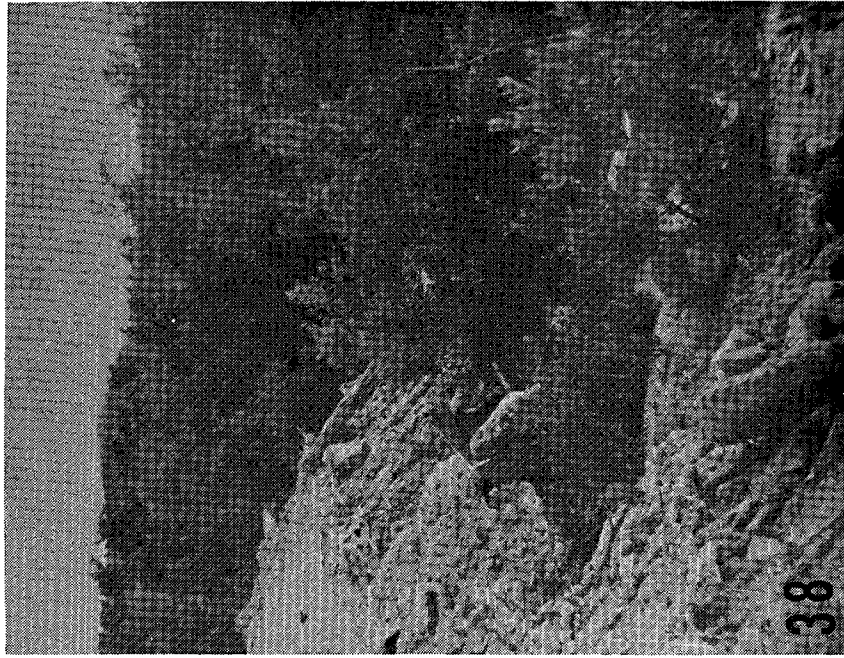


Figure 36. Mean low waterline along prop roots of red mangrove, Bovoni Passage. The roots provide shelter and habitat for juvenile fish and small lobsters.

Figure 38. Black mangroves buried by racetrack fill along north shore of the lagoon, March 1977. Loss of mangrove stands has contributed to decline of the area's natural resources.

Figure 37. Pneumatophores or aerial roots, of black mangrove are smothered by dense algal growths stimulated by excess nutrients; salt pond along western lagoon shore.





Discussion of Mangroves. Zonation patterns in the Mangrove Lagoon and Benner Bay system are similar to those observed elsewhere in the Caribbean. Fringe type mangroves are the dominant physiographic type. The successional development of these fringes is described in Cintron and Lugo (in press). This pattern may be summarized as follows: vigorous plant growth at the water edge results in a restriction to the flow of water into the inner parts of the swamp. Soil salinities in that part of the swamp increase and are invaded by the more tolerant species, Avicennia. However, eventually these trees may die as circulation is further restricted by active growth at the fringe and by clogging of drainage channels with prop roots and sediment. The low tidal energy available and reduced fresh water inflow cannot maintain the drainage channels open. Extensive areas of the inner swamp die and become salt flats.

This pattern may be reversed or slowed down by storms or periods of high precipitation. At that time the fringes may be partially destroyed allowing better circulation to the inner swamp by large water flows that can unclog or open new drainage channels. These conditions lead to a rejuvenation of the inner parts of the swamp.

Thus, a cyclic pattern is to be expected in xeric environments such as the Mangrove Lagoon. During periods following storms or high precipitation mangrove areas increase and salt flats decrease. During periods of drought, of storm free intervals, mangrove areas dwindle and salt flats increase. Failure to recognize this fact may lead to incompatible land use that may

affect the normal expansion of the mangrove forest during periods of low salinity. Thus, the salt flats are integral parts of the mangrove ecosystem and should be considered as such in any management scheme.

Comparison of the aerial photography available for changes within the last thirty years shows very little change, except for the extensive attrition in mangrove areas due to development in the edge of the lagoon. More surprising is the fact that little change if any is observable when old charts of the area are compared with the recent aerial photography and maps.

Mangroves have been considered active land builders (Davis, 1940). This classical view states that siltation on mangrove roots, and the resulting sediment aggradation, results in the formation of dry land. The fringes advance seaward into water made shallow by the growth of sea grasses. This picture may be applicable in areas where the coastline is accreting due to large sediment inputs; mangroves therefore colonize the shallows formed by physical processes.

In dry environments as the Mangrove Lagoon, however, where sediment inputs are small, where nutrient inputs are also small and productivity is low, the advance of mangroves into the open water is drastically reduced. Mangroves in this type of environment are opportunistic and will colonize sand bars and shallow areas formed by storms. Mangrove expansion elsewhere is limited by lagoon depth. Where the plantrites cannot become implanted because of excessive depth, colonization becomes exceedingly slow, since the biologic productivity is slow and the inputs of

of terrigenous and other sources of sediments are also small.

Over the long-term mangroves may be considered to be invading dry land, as sea level rises. If sedimentation offsets the rise in sea level the mangrove fringe will increase in size; if not, it will just shift landward. The change in sea level since the earliest charts of the area were prepared is small, less than 13 cm per century, and it may be assumed that it has resulted in minimal changes in the mangrove forest physiography.

Salinity and drainage play a dominant role in determining zonation and structural characteristics of mangrove forests. Alterations to drainage patterns can lead to the formation of evaporation ponds with extremely high salinities. These dense saline waters permeate the sediments and may remain well after the disturbance is removed. Salts may take years to leach away, especially in dry environments. Many salts accumulate in the flats by evaporation of ground water through upper layers. Attempts to replant or revegetate these areas would not be successful unless this fact is considered. Soil salinities must be appropriate or else replanting efforts are wasted.

An interesting characteristic of the mangrove lagoon area is the presence of two types of mangrove growth forms; a tall red mangrove forest and a dwarfed or low mangrove. As shown earlier excessive salt content of the soil water or surface water does not account for the "scrubbiness" of this forest. The tall mangrove forest occurs landward near sources of alluvial deposits. By contrast, the low forest occurs next to the barrier ridge (Bovonic Cay) formed by wave activity, far from the influence of

land-borne sediment and nutrients. This forest is flooded, and thus it is possible that nutrient accumulation is reduced as the leaching rate is high. These forests are also flooded by low nutrient sea water. It is suggested that the scrubbiness is due to adaptive factors and the greater nutrient loss due to tidal movement.

Benthic Biota. Results of the quantitative sampling program are summarized for the four seasonal sampling periods in Tables 12 to 16. The raw data, including an extensive list of annelids observed plus specimens and dried algae, are on file at the Island Resources Foundation.

Station 7 (Figure 3), which is just to the west of the most eutrophicated portion of Benner Bay, had standing crops of algae ranging from 1.4 grams wet weight to 60.95 grams wet weight. Stations 9 and 10A, which are in relatively clear water of the Halimeda-penicillus community showed increasing biomass of algae during the 12 month study period. In both cases the August samples were over 8 times heavier than the January samples and probably indicate peak summer productivity. The two stations of the inner Mangrove Lagoon (27A and 27B) gave conflicting results. Examination of the results reveal that several of the high figures appear to be due to sampling patch distributions of the algal community. This hypothesis was verified by diver transect observations (Figure 40). The greatest diversity and largest number of organisms was recorded from station 10A in the central lagoon. By contrast station 27A, which is close to a pollution source, has the least diverse flora and the lowest number of bivalves.

Table 12. Summary counts of the number of species and individuals in faunal samples from the Mangrove Lagoon and Benner Bay during August, 1976.

Five replicate samples at each station are lumped for totals. Asterisks are grab samples, others are cores. Number of individuals in a sample is followed by the minimum number of species in parenthesis.

| Major Group                            | 7*             | 9              | Station<br>10A | 11             | 27A*           | 50            |
|----------------------------------------|----------------|----------------|----------------|----------------|----------------|---------------|
| <u>Porifera</u>                        | -              | -              | 2(1)           | -              | -              | -             |
| <u>Coelenterata</u><br><u>Anthozoa</u> | -              | -              | 1(1)           | -              | -              | 1(1)          |
| <u>Platyhelminthes</u>                 | 1 0            | -              | - -            | -              | -              | -             |
| <u>Nematoda</u>                        | -              | -              | 175(1)         | 66(1)          | -              | -             |
| <u>Nemertea</u>                        | -              | 3(1)           | 1(1)           | 13(1)          | -              | 5(1)          |
| <u>Sipunculoidea</u>                   | -              | 1(1)           | -              | 149(1)         | 1(1)           | 1(1)          |
| <u>Bryozoa</u>                         | -              | -              | 3(1)           | -              | -              | -             |
| <u>Annelida</u>                        |                |                |                |                |                |               |
| <u>Polychaeta</u>                      | 139(8)         | 85(17)         | 236(20)        | 179(19)        | 114(14)        | 63(20)        |
| <u>Oligochaeta</u>                     | -              | 12(1)          | 8(1)           | 14(1)          | 9(1)           | 1(1)          |
| <u>Echinodermata</u>                   |                |                |                |                |                |               |
| <u>Holothuroidea</u>                   | -              | -              | -              | -              | -              | 2(1)          |
| <u>Arthropoda</u>                      |                |                |                |                |                |               |
| <u>Crustacea</u>                       | 1(1)           | 23(3)          | 146(11)        | 75(13)         | 63(6)          | 12(8)         |
| <u>Pycnogonida</u>                     | -              | -              | 3(1)           | -              | -              | -             |
| <u>Mollusca</u>                        |                |                |                |                |                |               |
| <u>Amphineura</u>                      | -              | -              | 5(1)           | -              | -              | -             |
| <u>Gastropoda</u>                      | 5(3)           | 100(4)         | 250(7)         | 76(10)         | 29(3)          | 1(1)          |
| <u>Pelecypoda</u>                      | 4(1)           | 4(2)           | 14(2)          | 17(5)          | 118(5)         | 13(3)         |
| <b>TOTAL</b>                           | <b>150(14)</b> | <b>238(29)</b> | <b>844(48)</b> | <b>589(51)</b> | <b>334(30)</b> | <b>99(37)</b> |

Table 13. Composition of  $\frac{1}{4}$  sq. m. quadrats collected in the Mangrove Lagoon and Benner Bay, January 28, 1977.

| Taxon                                                      | STATION      |                |                 |                 |              |
|------------------------------------------------------------|--------------|----------------|-----------------|-----------------|--------------|
|                                                            | 7            | 9              | 10A             | 27A             | 27B          |
| FAUNA, Numbers of individuals, (Minimum number of species) |              |                |                 |                 |              |
| <u>Annelida</u>                                            |              |                |                 |                 |              |
| Polychaeta                                                 | 0            | 20(2)          | 65(3)           | 0               | 0            |
| <u>Mollusca</u>                                            |              |                |                 |                 |              |
| Gastropoda                                                 | 1(1)         | 16(1)          | 4(1)            | 0               | 0            |
| Pelecypoda                                                 | 15(1)        | 11(3)          | 14(2)           | 6(3)            | 34(1)        |
| <u>Chordata</u>                                            |              |                |                 |                 |              |
| Ascidacea                                                  | 0            | 0              | 8(2)            | 0               | 1(1)         |
| Total number individuals                                   | 16(2)        | 47(6)          | 91(8)           | 6(3)            | 35(2)        |
| FLORA, wet weight, gms. (dry weight, gms.)                 |              |                |                 |                 |              |
| <u>Halophila</u>                                           | 0.3(0.1)     | 2.4(1.5)       | 0               | 151.3(11.3)     | 0.6(0.1)     |
| <u>Diplanthera</u> ( <u>Halodule</u> )                     | 0            | 49.5(9.2)      | 0               | 0               | 0            |
| <u>Halimeda</u> <u>incrassata</u>                          | 1.1(0.5)     | 0              | 0               | 0               | 0            |
| <u>H. monile</u>                                           | 0            | 0              | 2.3(0.5)        | 0               | 0            |
| <u>Caulerpa</u> <u>mexicana</u>                            | 0            | 3.2(1.5)       | 325.9(35.8)     | 67.5<br>(9.0)   | 0            |
| <u>Penicillus</u> <u>capitatus</u>                         | 0            | 0              | 13.9(5.6)       | 0               | 0            |
| <u>Acanthophora</u> <u>spicifera</u>                       | 0            | 1.2(0.3)       | 0               | 0               | 0            |
| Unidentified Rhodophyta                                    | 0            | 0.2(0.003)     | 0               | 0               | 0            |
| Total weight of plants                                     | 1.4<br>(0.6) | 56.5<br>(12.5) | 342.1<br>(41.9) | 218.8<br>(20.3) | 0.6<br>(0.1) |

Table 14. Composition of  $\frac{1}{4}$  sq. m. quadrats collected in the Mangrove Lagoon and Benner Bay, April 19, 1977,

| Taxon                                                      | STATION          |                 |                |        |
|------------------------------------------------------------|------------------|-----------------|----------------|--------|
|                                                            | 7                | 9               | 10A            | 27A    |
| FAUNA, Numbers of individuals, (minimum number of species) |                  |                 |                |        |
| <u>Porifera:</u>                                           | 3 (1)            | -               | -              | -      |
| <u>Annelida:</u>                                           |                  |                 |                |        |
| Polychaeta                                                 | 30 (1)           | 3 (2)           | 7 (1)          | -      |
| <u>Mollusca:</u>                                           |                  |                 |                |        |
| Gastropoda                                                 | 3 (2)            | 5 (3)           | 5 (1)          | 3 (1)  |
| Pelecypoda                                                 | 7 (4)            | 6 (2)           | 54 (3)         | 18 (4) |
| <u>Chordata:</u>                                           |                  |                 |                |        |
| Ascidiacea                                                 | -                | -               | 1 (1)          | -      |
| TOTAL NUMBERS                                              | 43 (8)           | 14 (7)          | 67 (6)         | 21 (5) |
| FLORA, Wet weight, gms., (dry weight, gms.)                |                  |                 |                |        |
| <u>Chlorophyta:</u>                                        |                  |                 |                |        |
| Caulerpa webbiana                                          | 0.07<br>(0.01)   | 0.24<br>(0.02)  | 4.64<br>(0.25) | -<br>- |
| C. cupressoides, f.<br>mamilliosa                          | -<br>-           | 15.74<br>(1.92) | -<br>-         | -<br>- |
| C. racemosa, f.<br>macrophyssa                             | -<br>-           | -<br>-          | 3.35<br>(0.22) | -<br>- |
| Acetabularia crenulata                                     | -<br>-           | 0.10<br>(0.03)  | -<br>-         | -<br>- |
| Halimeda incrassata                                        | 0.89<br>(0.11)   | -<br>-          | -<br>-         | -<br>- |
| Udotea flabellum                                           | 59.29<br>(22.77) | -<br>-          | -<br>-         | -<br>- |
| filamentous,<br>unidentified                               | -<br>-           | 5.83<br>(1.19)  | -<br>-         | -<br>- |

Table 14. (Continued)

| Taxon                  | STATION |        |        |        |
|------------------------|---------|--------|--------|--------|
|                        | 7       | 9      | 10A    | 27A    |
| <u>Rhodophyta:</u>     |         |        |        |        |
| Gracilaria cylindrica  | -       | 1.03   | -      | -      |
|                        | -       | (0.08) | -      | -      |
| <u>Spermatophyta:</u>  |         |        |        |        |
| Halophila              | -       | 0.05   | 9.90   | 0.59   |
|                        | -       | (0.01) | (0.96) | (0.11) |
| Diplanthera (Halodule) | -       | -      | 19.61  | -      |
|                        | -       | -      | (2.01) | -      |
| TOTAL WEIGHT OF PLANTS | 60.25   | 22.99  | 37.50  | 0.95   |
|                        | (22.89) | (3.25) | (3.44) | (0.11) |

Table 15. Total number of individual animals and plant species collected April 19, 1977.

|            | Number of Individuals | Percent of Total |
|------------|-----------------------|------------------|
| Porifera   | 3                     | 2.1              |
| Polychaeta | 40                    | 27.6             |
| Gastropoda | 16                    | 11.0             |
| Pelecypoda | 85                    | 58.6             |
| Ascidacea  | 1                     | 0.7              |
| Total      | 145                   | 100.0            |

|               | Number of Species | Percent of Total |
|---------------|-------------------|------------------|
| Chlorophyta   | 7                 | 70.0             |
| Rhodophyta    | 1                 | 10.0             |
| Spermatophyta | 2                 | 20.0             |
| Total         | 10                | 100.0            |

Table 16. Biotal composition of  $\frac{1}{4}$  sq. m. quadrats collected in the Mangrove Lagoon and Benner Bay, August 4 and 5, 1977.

| Taxon                                                      | Station  |        |        |          |      |
|------------------------------------------------------------|----------|--------|--------|----------|------|
|                                                            | 7        | 9      | 10A    | 27A      | 27B  |
| Fauna, Numbers of individuals, (minimum number of species) |          |        |        |          |      |
| <u>Annelida</u>                                            |          |        |        |          |      |
| <u>Polychaeta</u>                                          |          |        |        |          |      |
| Greater than 1 cm                                          | 71(2)    | 16(2)  | 4(2)   | 27(3)    | 0    |
| Less than 1 cm                                             | numerous | common | common | numerous | rare |
| <u>Mollusca</u>                                            |          |        |        |          |      |
| <u>Gastropoda</u>                                          |          |        |        |          |      |
| <u>Cantharus tinctus</u>                                   | 1        |        | 3      |          | 1    |
| <u>Cerithium literatum</u>                                 |          |        |        |          | 3    |
| <u>C. variabile</u>                                        |          |        |        |          | 7    |
| <u>Coraliophila aberrans</u>                               | 1        |        |        | 1        |      |
| <u>Bulla striata</u>                                       | 5        | 2      |        | 1        |      |
| <u>Cymatium sp.</u>                                        | 1        |        |        |          |      |
| <u>Modulus Modulus</u>                                     |          |        |        | 1        |      |
| <u>Marginellidae</u>                                       | 1        |        |        |          |      |
| <u>Phrgocythara coxi</u>                                   |          |        |        | 1        |      |
| <u>Taegulus divisis</u>                                    | 1        |        |        |          |      |
| <u>Engina sp.</u>                                          |          |        |        | 2        |      |
| <u>Pelecypoda</u>                                          |          |        |        |          |      |
| <u>Caecum pulchellum</u>                                   |          |        |        | 6        | 28   |
| <u>Chione cancellata</u>                                   |          |        |        |          | 2    |
| <u>Macoma sp.</u>                                          |          | 1      |        |          |      |

Table 16. (Continued)

| Taxon                                  | Station       |              |               |              |            |
|----------------------------------------|---------------|--------------|---------------|--------------|------------|
|                                        | 7             | 9            | 10A           | 27A          | 27B        |
| Flora, Wet Weight gms (dry weight gms) |               |              |               |              |            |
| <u>Algae</u>                           |               |              |               |              |            |
| <u>Chlorophyta</u>                     |               |              |               |              |            |
| <u>Avranvillea nigricans</u>           |               |              |               | 88.77(16.65) |            |
| <u>Halimeda opuntia</u>                |               |              |               | 1g (1g)      |            |
| <u>H. incrassata</u>                   |               |              | 54.55(14.52)  |              |            |
| <u>Caulerpa sertularioides</u>         | 125.54(11.56) | 3.44(0.11g)  |               |              |            |
| <u>C. mexicana</u>                     |               | 3.52(0.11g)  |               |              |            |
| <u>C. cupressoides</u>                 |               | 37.57(4.22g) |               |              |            |
| <u>Acetabularia crenulata</u>          |               |              |               |              |            |
| <u>Penicillus capitatus</u>            |               | 1g (1g)      | 399.06(75.85) |              |            |
| <u>Udotea flabellum</u>                |               |              | 16.70(4.98)   |              |            |
| <u>Rhodophyceae</u>                    |               |              |               |              |            |
| <u>Gracilaria cylindrica</u>           |               |              |               |              |            |
| <u>G. sp.</u>                          | 0.96 g        | 1g           |               |              |            |
| <u>Acanthophora speicifera</u>         | 28.2g(1.97g)  |              |               |              |            |
| <u>Unident Rhodeophyte</u>             |               |              |               |              | 0.1g(0.1g) |
| <u>Cyanophyceae</u>                    |               |              |               |              |            |
| <u>Lyngbya sp.</u>                     |               |              | 7.72g(1.56g)  |              |            |
| <u>Phaeophyceae</u>                    |               |              |               |              |            |
| <u>Dictyota divaricata</u>             |               |              | 0.1g(0.1g)    |              |            |
| <u>Spermatophyta</u>                   |               |              |               |              |            |
| <u>Halophila baillonis</u>             | 0.72g(0.1g)   | 46.96(5.87)  | 3.31(0.1g)    | 1g(0.1)      |            |
| <hr/>                                  |               |              |               |              |            |
| Minimum Annelid species                | 2             | 2            | 2             | 3            | 1          |
| Total Mollusc species                  | 6             | 2            | 1             | 6            | 5          |
| Total Plant species                    | 4             | 10           | 3             | 4            | 1          |
| Total wet wt. of plants                | 31.07         | 100.42       | 470.31        | 95.59        | 1.09       |

Three basic biotic associations occur in the Mangrove Lagoon and Benner Bay : (1) turtle grass flat, (2) sand filled channels, and (3) reef backs. In parts of the area, conditions of extreme turbidity, eutrophication, boat related turbulence and siltation have favored certain species from these associations over others. Therefore, at present there are at least eight recognizable communities which will be discussed.

The most widespread community over the past has been the turtle grass (Thalassia testudineum) dominated community. This extremely productive association is generally over 80 per cent dominated by this spermatophyte with regular appearances by another spermatophyte Syringodium filiforme and the Chlorophytes Halimeda, Penicillus, Avranvillea, and Udotea, (Fig. 41B). It acts as a juvenile habitat for many species of fishes and spiny lobsters. Over the past decade it is this community that has shown the most change.

McNulty, Robertson and Horton's 1968 benthic survey (Fig. 39D) seems to validate the assumption that the dark areas in the aerial photos represent Thalassia beds. If this is true, then the turtle grass beds have existed in their 1968 configurations since at least 1947. Tabb & Michel (1968) also support this finding. The area to the east of Bovoni Cay nearshore in Jersey Bay reconsolidated and expanded between 1947 and 1968. The first evidence of degradative change appeared in the 1968 survey (McNulty et. al., 1968; Fig. 39D) which shows the presence of a muddy bottom, generally devoid of plant life south of Middle Island in the Mangrove Lagoon and at the east end of Benner Bay. These

areas were previously covered by turtle grass. Grigg, et. al. (1971) shows increasing coverage of muddy bottom as do Olsen and Dammann (1973; Fig. 39E). The present effort (Figure 40) indicates that turtle grass currently has a very restricted distribution throughout most of the area. The eastern sector of Benner Bay is presently devoid of plant life. In many cases the turtle grass community has been replaced by or survived by an algal dominated community. The predominant forms are Halimeda and Penicillus the algae mentioned above as appearing in the grass flats. Other common components are the chlorophyte Acetabularia crenulata and various Caulerpa species, the Rhodophytes, Gelidium, Acanthophora spicifera, the Phaeophyte Dictyota divaricata, and the Spermatophytes Halodule and Halophila baillonis. The ichthyofaunal component is very similar to the small labrids, wrasses and lutjanids that one finds commonly over the turtle grass flats. The algal species are all found in the deeper sublittoral zone, evidence that they may be preadapted for the lower light intensities encountered in the higher turbidity waters that resulted from increased development in the surrounding watershed and from eutrophication. The benthic jelly fish Cassiopea has also increased greatly in population size over the recent years. They are frequently found within the Penicillus - Halimeda community on the bottom feeding photosynthetically. Presently almost all of the bottom in the Mangrove Lagoon, Bovoni Passage and much of Benner Bay is covered by these in a zone extending roughly 15 m from the mangroves.

In certain parts of the lagoonal complex, development

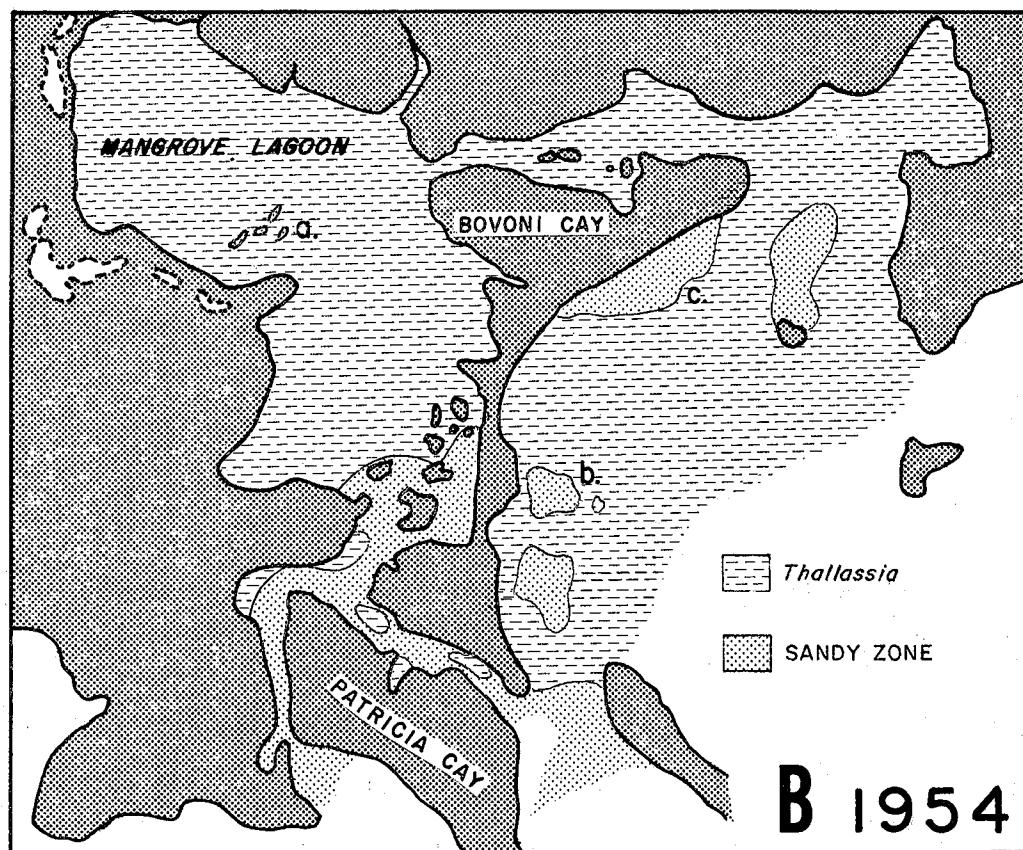
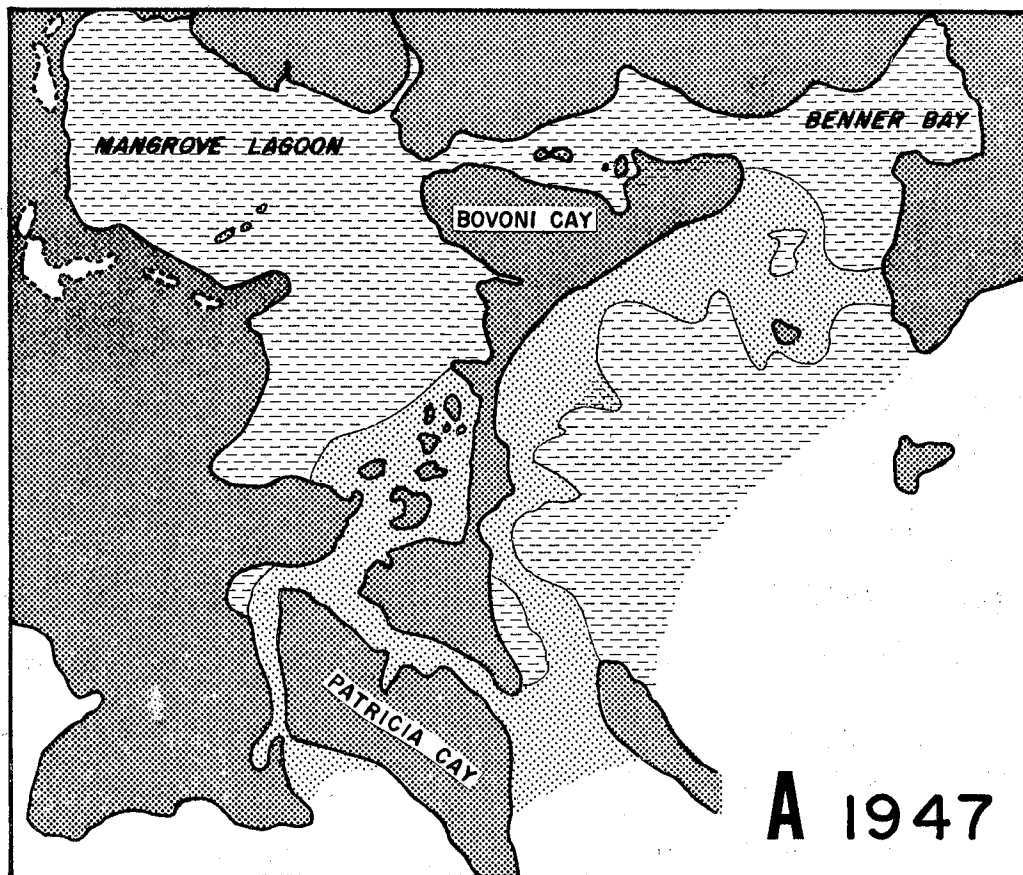


Figure 39. Distribution of major communities interpreted from aerial photography; A. 1947; B. 1954.

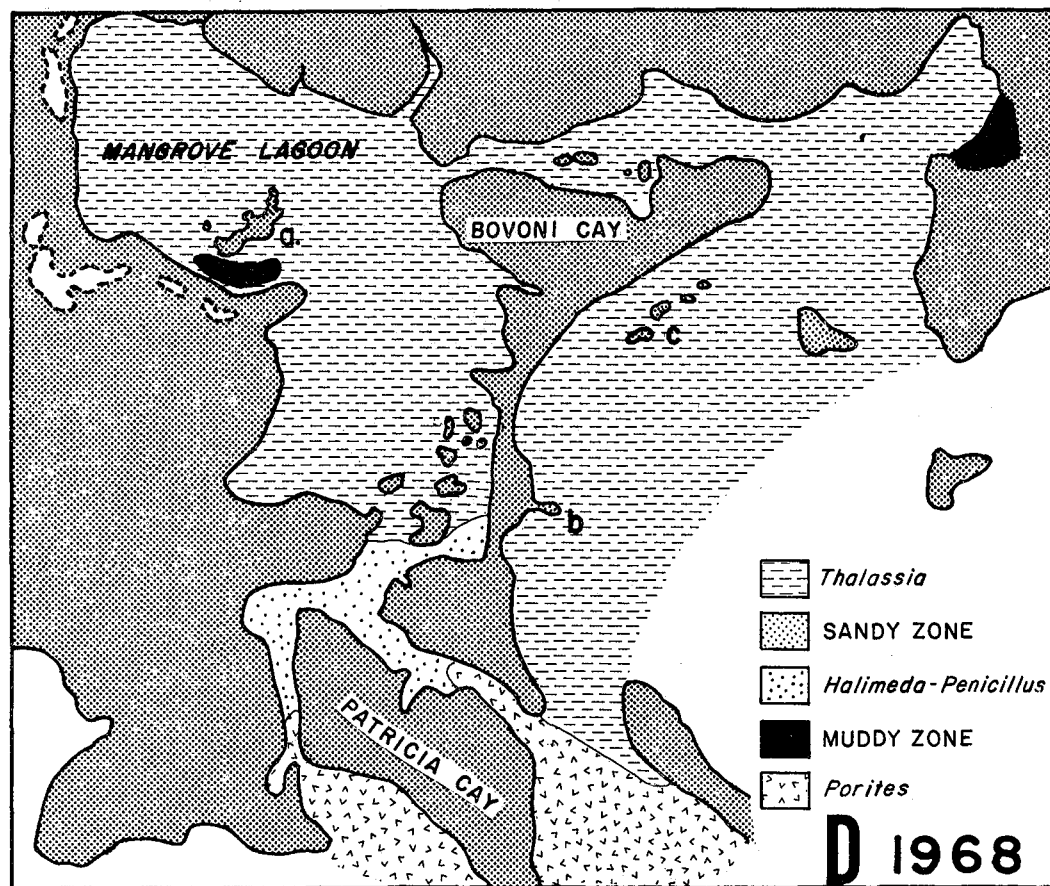
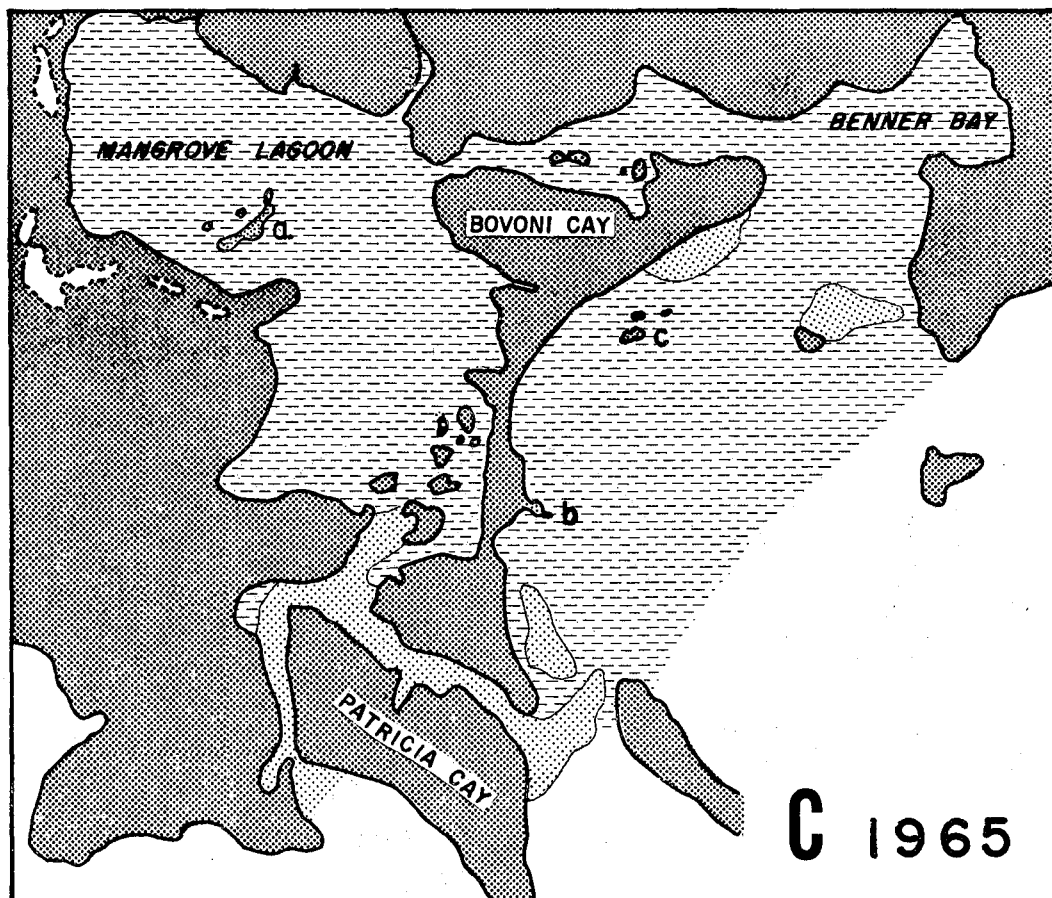


Figure 39. Distribution of major communities from: A. 1965 photography; B. McNulty (1968).

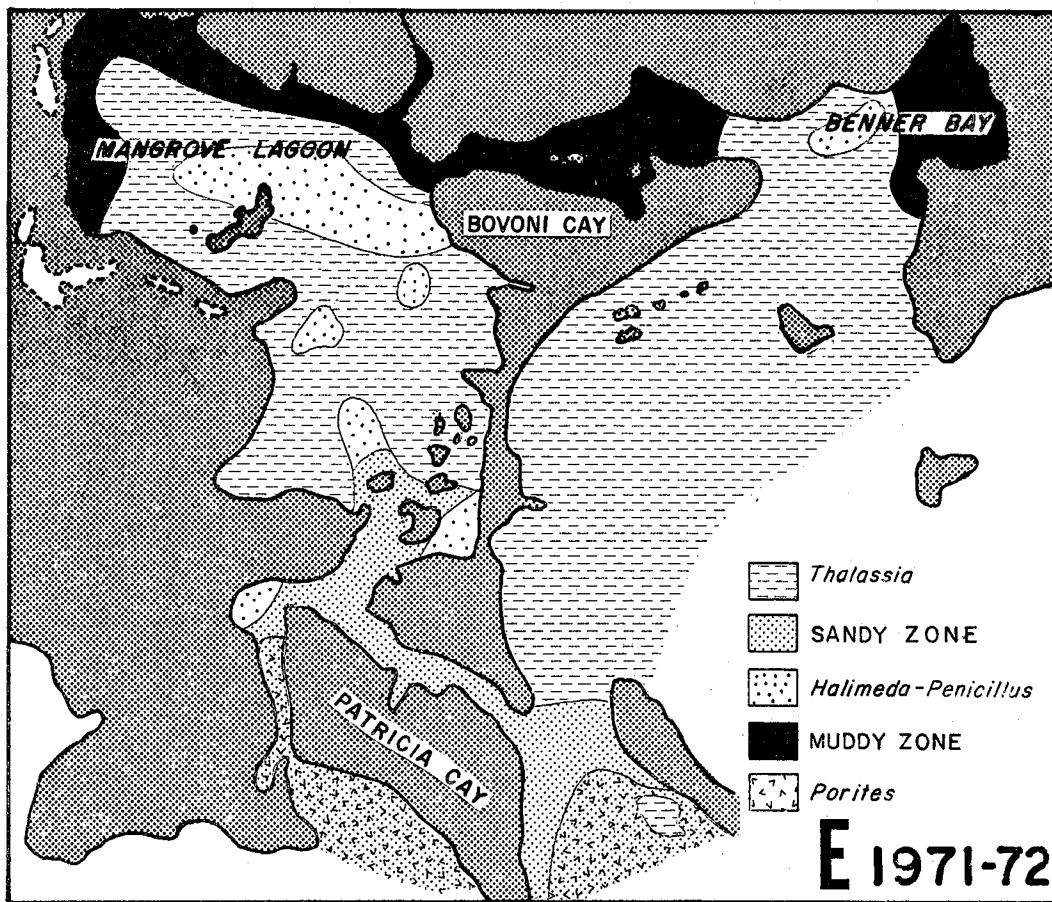


Figure 39E. Distribution of major communities from field observations of Olsen and Dumann 1971-1972.

related changes in water quality were apparently so great that the succession from turtle grass to algal domination in the benthic flora was bypassed completely. In these areas, the inner lagoon and eastern Benner Bay (Figure 40), heavy deposition of black organic detritus and nutrient enrichment led to the establishment of a loose semi-liquid sediment which came to be covered by the spermatophyte Halophila baillonis. This species has been shown to be tolerant of unstable substrates (Olsen and Sheen, 1974). It is a superior competitor in stressed situations but is easily displaced by other algal species when conditions permit their growth. The inner lagoon is covered with this community with about 90 per cent coverage by Halophila and occasional growths of Caulerpa cupressoides, Udotea falbellum and Avranvillea nigricans. This community extends through Bovoni Passage and is found in deeper parts of Benner Bay. The Halophila community appears to be the successor to the algal Halimeda-Penicillus community.

In the extreme eastern portion of Benner Bay, conditions have even surpassed those tolerated by Halophila. Two well defined zones of sabellid worms occur in this region. The first consists of scattered large individuals in the sediments themselves. The second zone is covered by a matrix of smaller sabellid tubes above the sediments. Algal cover does not begin until about 10 meters east of the channel itself. This strong zonation would seem to indicate that there is an intense gradient or change in the southeast sector of Benner Bay. Further investigation of the area may indicate a source in one of the commercial enterprises in the area.

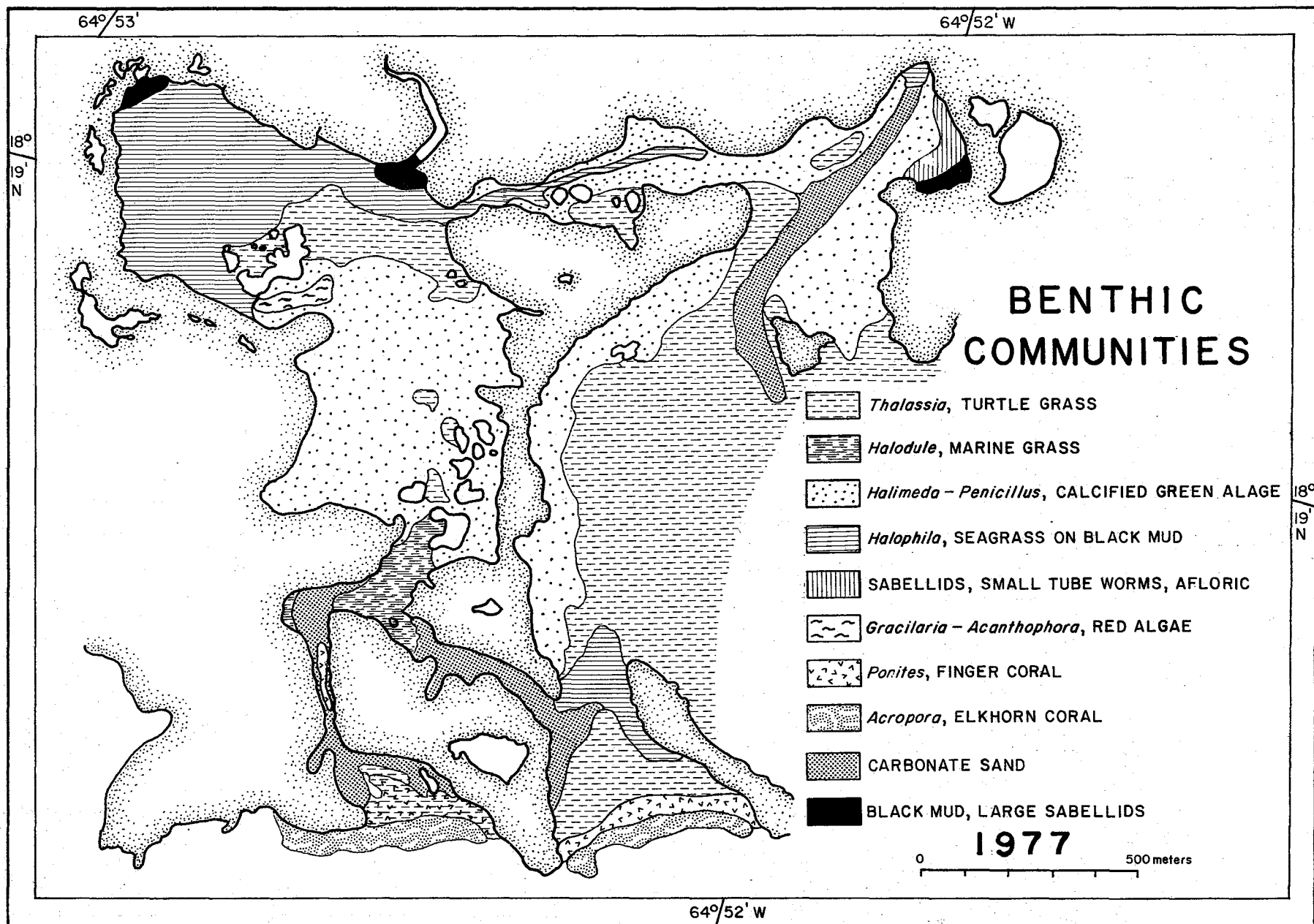


Figure 40. Distribution of benthic communities based on field observations of the present study, 1977.

It would appear that the successional sequence within the lagoon has gone from a "aboriginal" turtle grass to a community dominated by Halimeda and Penicillus, two species which occur normally as part of turtle grass beds. As light penetration became diminished by turbidity the algal community was restricted in its distribution and was survived by Halophila bailonis which has begun to cover much of the bottom in turbid reaches of the lagoon and to extend into the deeper parts of the Bovoni Passage. Concurrent establishment of this community in Benner Bay was not observed since intense eutrophication and high productivity resulted in conditions in which Halophila was unable to survive. There are two distinct zones of different sabellid worms in the southeast portion of the bay which indicate there is a steep gradient operating in this area.

Several other biotic associations were observed associated with the reefs in entrances and connecting channels of Patricia Cay. McNulty, et. al. (1968) show that the back reef community Porities extended through both of the entrance channels into the lagoon. Porites in Patricia Entrance was alive in 1971 but is almost completely dead at present. Current flow is very limited and eutrophic effects may be active. Dictosphaeria cavernosa is a relatively insignificant green algae which grows in secluded parts of the reef of the Atlantic and Pacific oceans. In the presence of eutrophication, its growth rate increases greatly and it forms thick mats which cover the entire bottom thus preventing light from reaching other components of the benthos (Maragos, 1972). Several samples of this algae collected from the Patricia Entrance channel

exhibit the beginning of this growth form. We suggest that the nutrient source may be the increased boat population at the western end of Cas Cay lagoon proper.

Immediately to the south of Middle Island in the Mangrove Lagoon, we found an area of fine sediment covered by the Rhodophycean algae Gracilaria cylindrica and Acanthophora spicifera. They occur in the area noted by McNulty, et. al. (1968) as one of the first occurrences of the black mud that has later come to be covered by Halophila. Both of these algae are commonly found in quiet back waters and may well be favored by conditions of heavy nutrient input, (Figure 41C).

Cas Entrance reach (Fig. 41A) was initially filled with Porites rubble and living corals (McNulty, et. al. 1968). Subsequent surveys have shown it to be covered with the Halimeda-Penicillus community (Grigg, et. al. 1971), turtle grass (Tabb and Michel, 1968) and a fine calcium carbonate sand (Olsen, et. al. 1973). Presently the fine sand covers part of the area while turtle grass and scattered algae cover the eastern portion. The major change in this area is a large and expanding area dominated by the spermatophyte Halodule and containing many small rhodophycean algae (Gelidium sp and several filamentous red algae). The aerial photos and field observations of the past five years also indicate that Halodule is expanding. Nutrient sources responsible for this change await further investigation.

The elkhorn coral Acropora palmata community dominates reefs between Patricia and Cas Cay (Figure 40) and around Rotto Cay. This community generally receives clear oceanic water

and survives in a relatively healthy state except where they are damaged by grounded boats and anchors,

Most people in the Virgin Islands are familiar with the statement that the "mangroves are a nursery ground for fishes and lobsters". This is only partly true. The Mangrove Lagoon is indeed an important nursery ground for fishes and lobsters, the only large extant system on St. Thomas. The mangroves themselves play an indirect role in the process in that their major input is probably detrital energy from their leaves and shelter in the root systems for small lobsters and two snapper species (Lutjanus griseus and L. apodus). In the presence of large nutrient inputs from pollution sources the mangrove contribution is proportionately less.

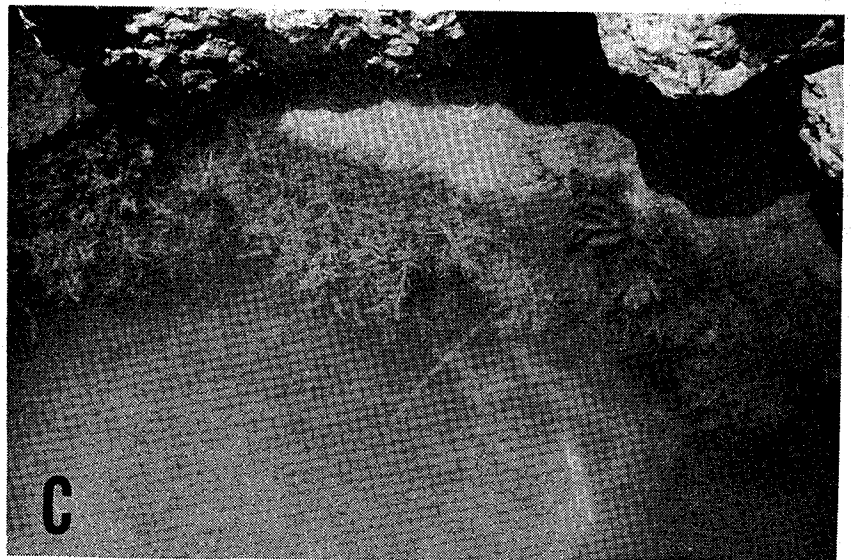
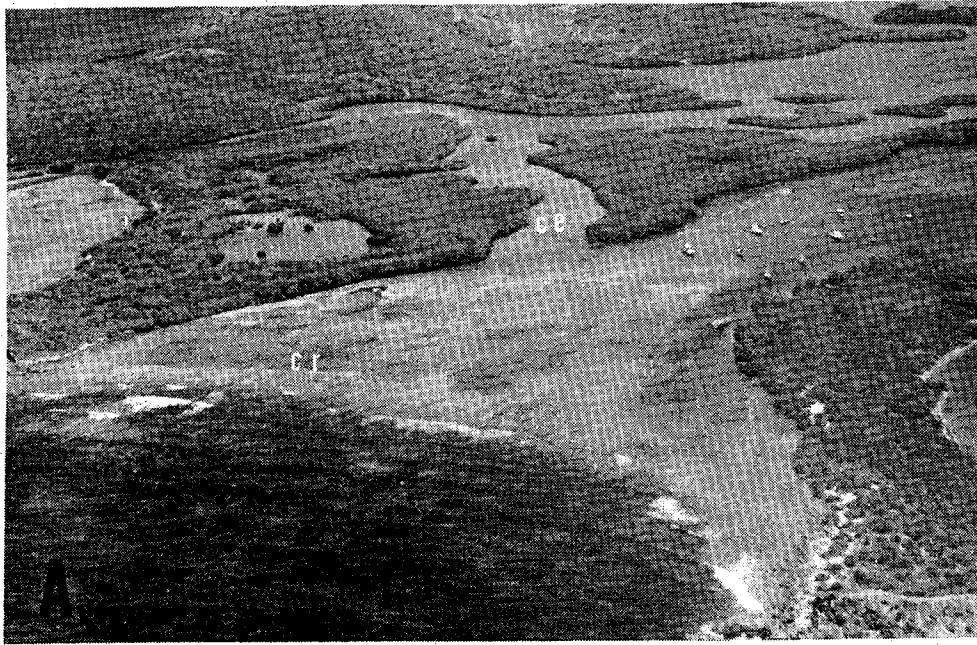
As can be seen from the analysis of the biotic succession in the area, this increase in nutrients from pollution and siltation is accompanied by a reduction and replacement of the turtle grass associated with the mangroves in the lagoon. This reduction has a significant impact on the lagoon as a nursery ground. Previous work documented that 93 percent of the lagoonal species found in the lagoon as juveniles are found in the reef environment as adults. Some of these juveniles continue to be found in the algal dominated community that succeeds the turtle grass but they are not found in any of the subsequent successional stages.

In summary, the mangrove lagoon that existed mainly in a natural state until at least 1968, contained large areas of turtle grass that survived until the early 1970's. At this time accelerated eutrophication and terrestrial sedimentation acted in

Figure 41A. Aerial view of back-reef flat community which lies landward of Cas Reef (cr); and a sand community, Cas Entrance (ce). The entrance is the main avenue of exchange between the lagoon and the sea. Wave transport over the reef drives seawater into the lagoon and through Bovoni Passage. Anchored boats threaten the entrance with sewage pollution, August 1977.

Figure 41B. Submerged turtle grass community in front of mangrove prop roots. The grass beds are rich and productive. They provide an essential habitat for many young fish and spiny lobsters. Less than 10 percent of the grass beds that once flourished in the lagoon remain intact.

Figure 41C. Submerged algal community attached to rock bulkhead in polluted zone of Bovoni Passage. Such algae thrive on excess nutrients, August 1977.



concert to restrict the distribution of turtle grass to the shallowest portions of the mangrove lagoon and began to eliminate it entirely from the Benner Bay area. The probable limiting factor was decreased light penetration resulting from increased turbidity. Turtle grass was survived by algal species, which are normally part of turtle grass beds (Halimeda, Penicillus, Avranvillea), and was invaded by a number of opportunistic species like Acanthophora spicifera (Doty, 1961). The resulting algal community provided a marginally suitable habitat for many of the juvenile fishes but its successor, the Halophila dominated association, did not. Surveys and conversations with fishermen reveal that during the late 1960's and 1970's, many of the schooling lutjanids (Ocyurus chrysurus, Lutjanus griseus, L. apodus) ceased to be abundant. These are three of the species which utilized the lagoon as a nursery ground (Olsen, et. al. 1973). We suggest that the present deteriorative trend within the one surviving juvenile habitat on the island of St. Thomas will have future repercussions in the offshore fishery.

## 10. Improving the Benner Bay Entrance Channel

Having determined the present condition of the water quality, sediments, biota and relevant processes in the bay, it remains to determine how the entrance channel can be improved without grossly altering functions of the bay or degrading water quality.

Benner Bay is intrinsically suited as a small craft harbor; it posses superb shelter and protection. The natural configuration and surrounding terrain offer access from the land as well as from the water. Protective structures are not required to deter wave action or sedimentation in the entrance. However, the bay lacks sufficient water depth in the entrance channel for deep draft sailboats. The chief aim is to gain maximum improvement with minimum disturbance.

At present the entrance channel into Benner Bay provides access for a width of about 18 m (68 feet) and a water depth of 1.4 m (4.5 feet) below mean low water. At high water and seasonal high tide between August and November, the water depth in the channel is about 1.75 m (5.6 feet). As shown in Figure 9, the main shoal across the channel is located between markers 9 and 10. Shoals also extend channelward at markers 7 and 8, a critical location where the channel changes course. Consequently, the channel is locally narrowed to less than 16 m (52 feet) at these points.

Comparison of water depths surveyed in the channel in 1970 (Zeigler) and in 1976 (present study) indicate that central parts of the channel are deeper by about 15 cm (0.5 feet) and shoaler on the sides by about 20 cm (0.6 feet) in 1976. Therefore, the channel

is narrower along the 1.1 m (3.5 feet) depth curve in 1976 than in 1970. This trend is most likely caused by propeller wash and dragging of keel sailboats through the channel. Reportedly, sailboats with drafts more than 1.8 m (6 feet) are hauled through the channel.

Bed sediments from outer parts of channel, between markers 7 and 9, consist of coarse muddy sand while from inner parts, between markers 9 and 11, they are mainly sandy mud. In general, mud becomes more abundant with distance landward into the bay. The upper 5 to 10 cm of bed sediment is moderately sorted by boat wash and has less silt and clay than at greater depth (10 to 60 cm). The sand consists mainly of calcareous particles of the algae Halimeda, mixed with scattered shell fragments. Most of the potential dredge material is poorly sorted and contains from 5 to 60 percent silt and clay. The sediment contains moderate amounts of toxic metals, leads, copper, oil and grease and nutrients. In general, the sediments become more contaminated with distance landward into the bay.

Probe depths indicate the sediment along the present channel course is "loose" and granular for more than 3 m (10 feet) below the sediment surface (Figure 17). No coral heads, rocks or consolidated sediment layers were encountered.

In short, the bed material is such that it can be easily dredged and disposed of. The muddy portion could create a local turbidity and contamination problem during dredging and disposal; however, the sandy portion would make good landfill.

Enlargement and deepening of the channel should conform to the natural bed geometry. This practice not only

minimizes the amount of dredged material but reduces future maintenance dredging. By following the natural bathymetry, disturbance of benthic habitats is kept to a minimum, natural slopes are partly retained and the natural pattern of water flow is largely preserved.

The channel depth required depends on the size and type of vessels using the channel and the speed at which they travel, a feature that governs the "squat" or sinkage into the water. Channel depths for dredging are commonly measured from mean low water. To attain a specified minimum controlling depth, it is practice to dredge 0.3 to 0.6 m (1 to 2 feet) deeper than the controlling depth, a practice that increases the volume of dredged material. Several hypothetical channel depths are considered to compare advantages and limitations of each.

One plausible plan considers a controlling channel depth of 2.4 m (8 feet) below mean low water with a 0.6 m (2 foot) overdepth, for a width of 30 m (100 feet) and a length of 925 m (3034 feet). Such a channel would extend along the course of the natural channel landward from the 2.4 m depth curve off Manglar Cay to Antilles Yachting Service at the bay head. It would provide water depth, shore access and passing room for large auxiliary sailboats more than 30 m (100 feet) long, and for inboard motor boats of more than 37 m (125 feet). Additionally, it would provide tacking room for sailboats up to 10 m (30 feet). These dimensions are extrapolated from average depth-length relationships used for approach channels and marinas (Appendix II, Adie, 1973). The "8-foot" depth would lower the existing depth of the channel floor

about 1 meter (3.3 feet). It would cut back side slopes 8 to 12 m (26 to 40 feet) and allow for straightening the alignment at markers 7 and 8. Dredging would cover an area of 27,750 m<sup>2</sup> and remove an estimated 22,050 m<sup>3</sup> (28,665 cu yds) of material.

Since deeper parts of Benner Bay floor are limited to less than 2.0 m (6.5 feet), anchorages would have to be dredged to accomodate morage of boats with 2.0 - 2.4 m (6.5 to 8 foot) drafts.

The 2.4 m (8 foot) depth plan would produce moderate changes in the natural bathymetry and lead to frequent maintenance dredging, possibly once every 2 to 4 years. The channel would act like a slot to trap sediment supplied from lateral shoals as well as from suspension in the overlying water. Infilling sediment would consist of high proportions of mud along with adsorbed contaminants. Dredging would increase the volume of inner Benner Bay about 10 percent and thus reduce the flushing a slight amount. Although sediment stirred up by propeller wash would be relatively small, there is a threat that turbid, toxic and nutrient-rich materials would be released during initial dredging and disposal of muddy sediments from inner reaches. In brief, an 8-foot plan would provide a great improvement with moderate disturbance. It would create a substantial amount of dredged material to be disposed of.

A controlling channel depth of 1.8 m (6 feet) below mean low water in addition to 0.3 m (1 foot) overdepth, for a width of 24 m (80 feet) and a length of 330 m (1100 feet) would provide depth for most auxilary sailboats of 13.5 m (45 foot) length and 4.5 m (15 foot) beam (without tacking space). Additionally, it would provide depth for most inboard motor boats over

30 m (90 feet) long and for all outboard boats (Appendix II, Adie, 1975). The "6-foot" depth would lower the average depth of the existing channel floor 20 cm (8 inches). It would cut back side slopes 4 to 10 m, eliminate lateral shoals and the 1.4 m sill, or threshold, between markers 9 and 10. At the same time a straighter alignment than the present channel could be attained at marker 7. Dredging would cover an estimated area of 7,920 m<sup>2</sup> and remove an estimated 9,722 m<sup>3</sup> (12,639 cu yds) of material.

The 1.8 m (6-foot) depth plan would improve the existing channel and follow bathymetry of the natural channel over most of its course. Large changes in the alignment and thus the direction of flow could prove difficult and costly. Since the inner bay floor has depths greater than 1.8 m, the channel would terminate 75 m landward of marker 9. It would not cut into the inner part of Benner Bay and thus affect the flushing volume. Maintenance dredging would be required infrequently, possibly once every 3 to 5 years, to remove infilling sediments from the sides. The 1.8 m (6-foot) plan would have very little affect on flushing of pollutants from Benner Bay, Bovoni Passage or the Mangrove Lagoon.

The existing cross sectional area of the entrance is already more than adequate to handle the relatively weak tidal exchange. In brief, a 6-foot plan would provide substantial improvement with minimum disturbance.

An alternate plan for relatively deep draft boats is to provide an access channel, anchorage and shore facilities in a seaward area close to deep water. This would include a deep but short channel through East False Entrance and berthing along the west shore of Compass Point. The existing channel, or a 6-foot depth plan, could provide access for small boats into Benner Bay while a tributary channel into Bovoni Passage could serve shore facilities along Bovoni Passage as well as access to storm refuge zones behind Bovoni Cay.

A problem in dredging entrance reaches is disposal of the dredged material. Normally, dredged material is disposed of in the most economical way with minimal environmental disturbance. The most economical way is to dump the material alongside the dredged channel. This requires no hauling or transportation but the material may bury habitats, create turbidity, spread over adjacent grass beds and backfill the dredged channel creating high maintenance costs. The dredged material should be dumped outside the environs of Benner Bay, Jersey Bay and the Mangrove Lagoon. Dumping at sea may be feasible if the material meets EPA criteria for ocean dumping of July 1977. On the other hand, the material is sufficiently sandy especially in seaward parts of the channel, to make good fill on upland areas. It may be necessary to dump it behind dikes to prevent release of contaminated silt and clay. At present criteria for upland disposal are in a state of flux. It is difficult to determine whether a given sediment contains sufficient contaminants to warrant alternate methods of disposal.

11. Summary of Scientific Findings and Their Significance for Management.

A. The basins occupied by the Mangrove Lagoon and Benner Bay began to form more than 5,000 years B.P. when the region was downfaulted and cut by streams during lowered sea level. About 4,500 years B.P. when sea level rose to 5 m, waves built Bovoni Cay and thus formed the lagoon behind it. The cay continues to build as mangroves clog washover passages and stabilize seaward extending shoals. At the same time, sedimentation, shoaling and pond closure are contracting the inner lagoon. Such processes have been speeded up in recent years by man.

A significant change in the shore configuration or bottom geometry of the natural basin may be detrimental to the circulation, water quality and ecology. Dredge and fill plans should be carefully evaluated for potential ecological effects and consistency with protective management. Channels should be designed to gain maximum improvement with minimum disturbance. In general, they should be kept to minimum size and located to avoid vital habitats.

Deepening the Benner Bay entrance channel to the 1.8 (6-foot) depth is feasible. The channel should be laid out to follow the existing natural bathymetry. Maintenance dredging would be infrequent and would remain so if pollution is abated and future disturbance in the area is minimal. Disposal of dredged material needs to be accommodated with regard to its toxic substances, volume and content of fine sediment. Deepening would not alleviate pollution and poor water quality in the bay.

Any effort to reduce sedimentation will prolong life of the lagoon and bay. Fine sediments are of special concern because of their secondary effects in creating turbidity and transporting

toxic substances. The relevant management practice is to avoid sediment accumulation by controlling sediment at its source. This means tight controls through the Earth Change Law, on all development in the watershed; particularly those activities that expose soil or alter drainageways by excavation, grading or land clearing. This means the V.I. Department of Public Works should practice the law, just as citizens do, on government property around the racetrack and municipal dump. The degree of constraint should be determined by: (1) proximity to the water (2) sensitivity of the environment, (3) magnitude or extent of the potential disturbance.

Because vegetation in sloughs, washes and flood plains tends to filter out sediment and modulate flash flooding, natural drainage channels should be preserved. Construction of reservoirs and ponds in headwaters should be encouraged.

B. Four modes of circulation were observed: (1) a broad clockwise pattern driven by ocean wave transport across the Cas-Patricia Cay reefs, (2) a weak reversing tidal current mainly through Benner Bay entrances, (3) a local wind drift and (4) a short-term stream runoff through all entrances. The lagoon and bay are flushed adequately only during periods of spring tide range and high wave transport over the reefs. Current speeds generally diminish inward toward the lagoon head. During mean range of the tide, approximately 19 percent of the lagoon water is exchanged with Jersey Bay. However during neap range of the tide, light winds and low waves over the reef, the circulation is virtually inoperative.

Ecological health of the lagoon and bay depend upon active

flushing and exchange with Jersey Bay. Any change in the geometry of entrance passages that reduces flow is presumed detrimental and should be avoided. Prospective activities that may alter the natural circulation, and presumed to be adverse, include: (1) realigning or narrowing entrance channels, (2) altering passes by bridges, causeways and jetties, (3) retarding flow by mounds of dredged material, (4) altering shoreline configuration with piers and landfill structures. Inner reaches of the lagoon and bay are particularly sensitive to changes in water depth and configuration.

C. Most salt ponds, marginal lagoons and intertidal backwaters have restricted drainage. Many ponds are flushed only during spring tide or seasonal high tides (July through November). Geologic and biological evidence indicates the ponds were once well-flushed by the tide and they were connected to the lagoon's hydrologic system. Without adequate flushing, salinity increases during dry periods, sediments become anoxic and mangroves suffer or die. This trend is exemplified by the Compass Point salt pond east of Benner Bay where drainage is restricted by a roadway. Closure of this pond has not only killed the mangroves but reduced the tidal prism of inner Benner Bay about 33 percent. In turn, flushing of the bay is reduced about 20 percent further extending the residence time of pollutants.

The pond west of the treatment plant landward of the lagoon head, is restricted by debris, mangrove roots and a roadway along the northeast side. Mangroves are dying out, nutrients are excessive, algae are abundant and sediments are black and anoxic.

The ponds are not only sensitive to changes in tidal exchange but to alterations in adjoining salt flats and upland

drainage.

The relevant management practice is to avoid changes in the flow of water between the ponds and the lagoon that restrict or block exchange. This requires restrictions on filling, waste disposal, dikes, weirs, piers, bulkheads, causeways, bridge and channel modification in and around salt pond that block or impede passage of water. Upper limits of tidal flooding around landward margins of the ponds should be surveyed to establish the bounds of public property and to serve as a basis for establishing a protective buffer zone. Such a zone should extend from the upper limits of tidal flooding to an elevation of 0.5 m above the tidal limit so as to include contiguous salt flats and lower parts of stream drainage. The buffer should be designed not only to restrict landfill and waste disposal but to control local alteration of entering streams courses.

D. Water quality is generally good with respect to temperature salinity and pH. However, inner reaches are turbid (> 2 JTU) and oxygen saturation is less than 50 percent under "worst case" conditions. Gross production of the inner lagoon is very high, 8 to 10 times greater than in entrance reaches. Toxic metals in the sediments, copper, lead and zinc, plus oil and grease are higher than normal. Concentrations in sediments and ground water lagoonward from the municipal dump are seriously high.

Pollution of the bay is caused by sewage from boats and diffuse sources in the watershed and on the waterfront. In the lagoon, pollution is caused by nutrient-rich runoff from Turpentine Run and by an overloaded, malfunctioning and obsolete sewage

treatment plant. The excess supply of nutrients combined with weak water circulation in the lagoon, lead to eutrophication (over-fertilization) and rapid growth of phytoplankton.

The relevant management practice is to eliminate discharge of sewage effluents at their source: boat discharges, diffuse sources, and an overloaded, malfunctioning and obsolete treatment plant. Most land-borne or waterfront sources can be controlled by existing ordinances. Marinas should incorporate better facilities for handling sewage, refuse, wastes and bottom scrapings. Live-aboards on boats without holding tanks or treatment facilities, should be moored in protected zones of Jersey Bay where flushing is better than in Benner Bay. The influx of nutrients from the watershed, especially nitrogenous wastes, into the lagoon via streams as Turpentine Run should be reduced. Diffuse or "non-point" sources as fertilizers should be identified and brought under control. Any control of fine sediment from residential or agricultural areas in the watershed would also probably reduce influx of nutrients and toxic substances.

E. Since 1968, over 90 percent of the turtle grass beds that once flourished throughout the lagoon have been destroyed. Less than 10 percent remain. They are survived by extensive growths of benthic algae Halimeda, and by the seagrass Halophila which lives on black mud. Most shellfish (bivalves) are reduced in number, while polychaetes (Sabellid worms) and benthic jelly fish (Cassiopea) have invaded a wide area of inner zones. The lagoon head, mouth of Turpentine Run and eastern Benner Bay are devoid of benthic life. The greatest impact of pollution on benthic life is felt in inner zones close to sewage sources where circulation and exchange is least.

Any effort to eliminate pollution, reduce sedimentation and improve water quality and circulation would be an obvious benefit to stall the decline of benthic life. In particular, higher than normal levels of turbidity can be reduced by retarding growth of phytoplankton through nutrient control and by eliminating discharge of turbid materials, pollutants and sediment at their source. Eroding shores, though a secondary source, should be stabilized. Boat traffic across shoals that stirs up mud and rips out grass beds, should be controlled. Sources of oxygen-demanding contaminants as organic matter of various sorts, released into the water, should be eliminated. Accidental spills are especially hazardous because they impair oxygen exchange with the atmosphere and are impossible to clean up in mangrove thickets. Controls should be developed for safeguards and precautions.

It is essential that remaining grass beds, nursery areas and breeding grounds and vital habitats be insulated and free of human disturbance.

F. An estimated 15 percent of the mangrove areas are dead or in stages of dying. Since these areas are an essential natural resource--the largest mangrove lagoon remaining in the Virgin Islands--they should be protected by placing them in the territorial park system.

Any activity or structure that changes the natural drainage or salinity of the mangrove areas should be avoided. Above all, the mangroves should not be cut, removed or obliterated except to improve drainage and circulation in other parts of the mangrove stands. Mangroves serve best as a natural system providing shore protection and stabilization, nursery areas, breeding grounds

maintenance of water quality and supportive shelter for fish and wildlife.

## 12. Prospect

What will the lagoon and bay be like in the next five years if present trends continue? An ever-increasing number of boats growing number of people and waterfront facilities will increase the potential for pollution. Sewage pollution will intensify in inner reaches as facilities and waters become overloaded. Turbidity will be further increased and oxygen depleted. Lagoon water will become foul with noxious odors, decaying algae and hydrogen sulfide. The black mud blanket with zones devoid of benthic organisms will spread throughout inner reaches of the lagoon and bay while the remainder of the area will be covered with polychaete worms. Effects of sewage pollution will spread farther seaward than at present, encroaching on Manglar Cay, south end of Compass Point and to back-reef areas of Cas and Patricia Cays. Diffuse sources of pollution along the waterfront and in the watershed will become relatively more important. Subtle chemical pollutants and hydrocarbons released from boats, trash, fuel spillage and an active racetrack may cause unexpected damage to mangroves and remaining grass beds. In short, the lagoon and bay appear doomed as a natural system. With its demise, a significant natural and recreational resource for Virgin Islanders will be lost.

Present trends of environmental deterioration can be stalled by sound conservation practices. Conservation and protection are the key to maintaining a healthy environment. Some problems can be resolved by better enforcement of existing regulations. Other

problems can be ameliorated by better planning and coastal management. A great deal is now known about how the environment operates and some good laws exist to control it. Putting the knowledge and laws to work now depends on active and concerned citizens and success of the coastal zone management program.

### 13. Recommendations

A. Changes in the configuration and bottom geometry of the lagoon and bay should be avoided unless absolutely necessary and until prospective ecological effects are carefully evaluated. Deepening the Benner Bay entrance channel to 1.8 m (6-foot) can be accomplished if plans meet environmental guidelines for dredging and disposal including toxic substances.

Sedimentation should be reduced by control of sources: (1) erodable areas of the watershed (2) production of calcareous algae and phytoplankton. Eliminating pollution sources and hence nutrient supply, would retard algae growth.

B. Circulation throughout the lagoon and bay should be maintained by avoiding major changes in configuration, bottom geometry, or structures that restrict flow. The circulation could be improved by widening the "narrows" between Bovoni Passage and the lagoon. Additionally, exchange between Jersey Bay and the lagoon could be improved by removing Porities rubble from Patricia Cay entrance channel. The influx of seawater into the lagoon should be increased by removing rubble from shallow inlets through the reef crest on the Patricia and Cas Cay reefs. Additionally, inlet-washover channels through Bovoni Cay, which are clogged by debris and mangroves roots, should be re-opened.

C. Salt pond water quality and habitat should be improved by allowing normal tidal flow into the ponds. Restrictive structures like roadways and dikes should be opened to allow flow of tidal water. Waste disposal and landfill around pond margins and on high flats should be prohibited. Tidal exchange of ponds around west, north and east margins of the lagoon and bay can be improved by manually clearing entrance channels into and between ponds. Where mangrove roots are extensive, alternate channels should be established to connect the pond with the lagoon in a short distance. All openings should be shallow, 0.3 m below mean low water at the most. They should be accomplished manually by pick and shovel without heavy construction equipment.

D. Pollution should be more tightly controlled at known sources. Diffuse sources along the waterfront and in the watershed should be specifically identified and controlled immediately. These include leaching or malfunctioning septic tanks, local gas and oil spills around marinas, restaurants, bakeries, fuel docks, and hotels. High density boat berthing with "live-aboards" along inner reaches of Bovoni Passage and Benner Bay should be replaced by dispersed moorings more than 30 m (100 feet) apart. Additional moorings should be provided in sheltered areas of Jersey Bay. The Nadir treatment plant should be abandoned and replaced by an ocean out-fall suited to rapid diffusion and dilution. Solid wastes, trash, debris and junk autos should be removed from flats and pond margins. As previously indicated these areas are an integral part of the lagoon system and require a marginal buffer zone around landward

margins. Both surface and subsurface drainage from the municipal dump should be restricted.

E. Pollution and sediment sources damaging to benthic life should be brought under control immediately. No wastes or contaminants of any kind should be discharged into the lagoon or inner reaches of Bovoni Passage and Benner Bay. Efforts to improve water quality and circulation through management practices previously noted are highly recommended.

F. Mangroves should be protected from significant alteration by (1) zoning, (2) a buffer zone on landward sides, and (3) by protection overall, together with ponds, flats and the lagoon itself, in a territorial park system. Cutting of shoreline mangroves or trails through the mangroves for boat moorings or for any purpose other than the planned area management and use program should be prohibited. The Mangrove Lagoon should be reserved as a wildlife resource with recreational and sport fishing activities in designated areas as shown in Figure 42.

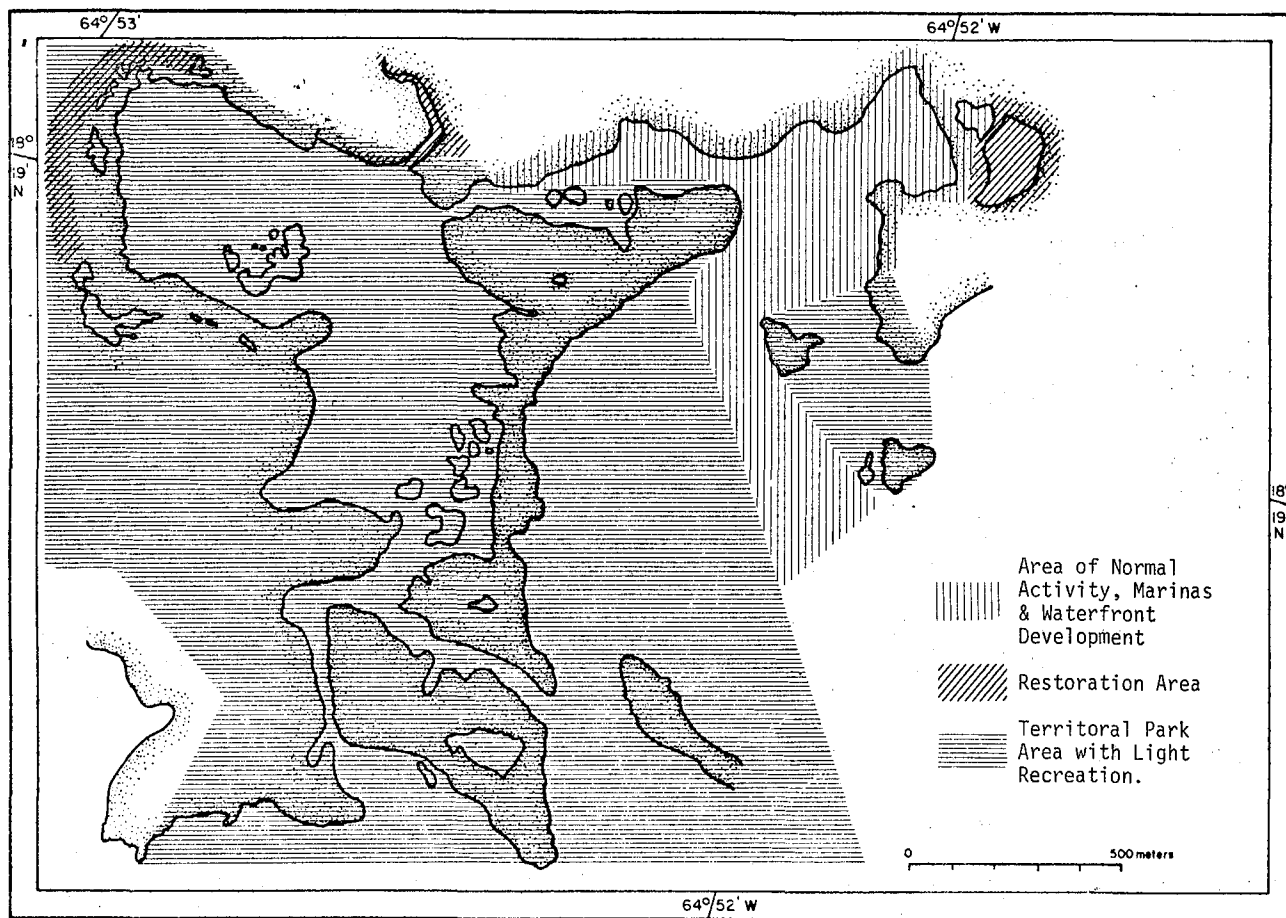


Figure 42. Proposed designated uses of the region for future management.

#### 14. References

- Adie, D. W. 1975. Marinas, a working guide to their development and design. Architectural Press, LTD. London, 336 p.
- Cintron, G. and A. E. Lugo (in press) Mangroves of arid environments in Puerto Rico and adjacent islands. Forthcoming Biotropica.
- Dammann, A. E. et al. 1969. Study of the fisheries potential of the Virgin Islands. Caribbean Res. Inst., Col. of the V.I., VIERS Contribution No. 1.
- Davis, J. H. 1940. The ecology and geologic role of mangroves in Florida. Papers from Tortugas Lab. No. 32, Carnegie Inst. Wash. Publ. V. 517, p. 305-412.
- Donnelly, T. and Whitten, J. 1968. Field guide to the geology of the Virgin Islands. Fifth Caribbean Geological Conference.
- Doty, M. S. 1961. Acanthophora spicifera, a possible invader of the marine flora of Hawaii. Pac. Sci., Vol. 15, p. 547-552.
- Francois, P. A. and Brown, V. C. 1975. Report on Water Quality, Virgin Islands, United States of America, 1970-1975. 25 pp.
- Grigg, D. I., vanEepoel, R. P. and Brody, R. W. 1971. Water Quality and environmental status of Benner Bay-Mangrove Lagoon, St. Thomas. Water Pollution Report No. 10, Carib. Res. Inst., Col. of the V.I., 42 pp.
- Grigg, D. I. and vanEepoel, R. P. 1972. Status Report on bays of St. Thomas and St. John. Virgin Islands, Water Pollution Report No. 19. Carib. Res. Inst., Col. of the V.I., 30 pp.
- Helz, G. R., Huggett, R. J. and J. M. Hill, Behavior of Mn, Fe, Cu, Zn, Cd and Pb Discharged From a Wastewater Treatment Plant into an Estuarine Environment. Water Res. 1975, Vol. 9, pp. 631-636.
- Insular Environments. 1975. Environmental Reconnaissance Surveys of Selected Bays. Report to the V.I. Dept. of Cons. & Cult. Affairs, 31 pp.
- Insular Environments. 1975. Environmental Study Report for Proposed Docks, Bulkhead and Walkway at Benner Bay, Antilles Yachting Service, 42 pp.

- Island Resources Foundation. 1976. Virgin Islands Coastal Zone Management: the Marine Environment, Report to the Virgin Islands Planning Office, 190 pp.
- Jordan, D. G. and Cosner, O. J. 1973. A survey of the water resources of St. Thomas, Virgin Islands. U.S. Geol. Survey, Open file report, Caribbean District, 55 pp.
- Lugo, A. E. and G. Cintron. 1975. The mangroves of Puerto Rico and their management. in G. Walsh, S. Snedaker, and H. Teas (eds.) Proc. Int. Symp. on Biol. and Management of mangroves. Inst. Food Agr. Sci., Univ. Fla., Gainesville. pp. 825-846.
- Maragos, J. E. 1972. A study of the ecology of Hawaiian reef corals, Thesis, University of Hawaii, Honolulu, Hawaii.
- McNulty, J. K., Robertson, W. B. and Horton, B. F. 1968. Departmental study team report and recommendations on proposed new jet airport, St. Thomas, U.S. Virgin Islands, 34 pp.
- Michel, J. F. 1970. A study of the hydrodynamic effects of the proposed airport at Long Beach Point, St. Thomas. Consulting Report by University of Miami: to the Virgin Islands' Port Authority.
- Odum, H. T. and C. M. Hoskins. 1958. Comparative Studies on the Metabolism of Marine Waters. Texas, Inst. of Marine Science, Vol. V, p. 16-49.
- Olsen, D. A. and A. E. Dammann. 1973. The ecology of fishes in two mangrove lagoons in the U.S. Virgin Islands. Puerto Rico International Underseas Lab., Spec. Rpt., 42 pp.
- Olsen, D. A., and M. O. Sheen. 1976. A study of a Puerto Rican Coral Reef System. Hydrolab Journal 3(1):108-113.
- Rivera, L. H., McKinzie, W. E. and Williamson, H. H. 1966. Soils and their interpretations for various uses, St. Thomas, St. John, Virgin Islands, U.S. Dept. of Agriculture, S.C.S. 51 pp.
- Tabb, D. C. and Michel, J. 1968. A study of the biological and coastal engineering aspects of the proposed jet airstrip at Jersey Bay, St. Thomas, U.S. Virgin Islands. Consultant Report by the University of Miami to the Office of the Governor, U.S. Virgin Islands.

## 15. Acknowledgements

The work was accomplished as follows: Gilberto Cintron of the Department of Natural Resources, Commonwealth of Puerto Rico, surveyed botanical features of the mangrove forests and contributed the section on mangrove studies; David Grigg of Sigma Environmental Sciences, surveyed the benthic biota in January and April, 1977; Robert Huggett of the Virginia Institute of Marine Science analyzed chemical constituents of the sediments; William Rainey of the Island Resources Foundation initiated the benthic biology study in July 1976, assisted by Mark Silverstein, Norman Selesky and Robert Teytaud; David Olsen surveyed the benthic biota in July and August 1977 and digested all the earlier biological results for this report; Edwin Rosenberg (Rear Adm., USN and VIMS graduate student) accomplished most of the core studies together with Adam Frisch, VIMS graduate student; Galen Thompson surveyed the bathymetry, shoreline and water quality assisted by Richard Trotman, A. Gumbs and Lucy Foster. Nichols put the pieces into a coherent format and edited the final report between numerous diversionary activities. Edward Towle simplified administration and blessed the study with his wisdom and editorial counsel throughout.

We thank Judith Towle for an accurate monitoring of fiscal matters and for a final editorial review. Kathleen Finnerty and Teresa Wilburn converted rough drafts into reports while Peggy Peoples and Jane Davis drafted the figures. Michael Grogan of the DCCA Water Pollution Lab provided field assistance and analytical services.

We thank John Woods of the Virgin Islands Port Authority, Fred Fehling of Antilles Yachting Services, Arthur Dammann of the Bureau of Fish and Wildlife and John Michel of the University of Miami for advice and historical information. Equipment and analytical services were provided by the Water Pollution Laboratory, Department of Conservation and Cultural Affairs, St. Thomas. The study was supported by funds from the U.S. Environmental Protection Agency through a contract from the Virgin Islands Department of Conservation and Cultural Affairs, Viridin C. Brown, Commissioner, and Pedrito Francois, Director, Division of Natural Resources Management. Mr. Robert Van Eeepoel of DCCA served as general program manager.

## APPENDIX I

Chemical procedures for analyses of sediments and ground water.

### Total Volatile Solids (%TS, %VS)

The sediment samples were dried in an oven at 103<sup>0</sup> to constant weight, (dry weight/wet weight x 100 = percent total solids). The dried samples were placed in a muffle furnace for one hour at 550-600<sup>0</sup>C. The decrease in weight after ashing was reported as volatile solids.

### Chemical Oxygen Demand (COD)

The parameter was determined by the dichromate reflux method. The oxidizable substances were oxidized by a standard solution of potassium dichromate in sulfuric acid. The excess dichromate was titrated with standard ferrous ammonium sulfate. Silver sulfate was used as a catalyst; mercuric sulfate was used to eliminate the interference to chloride ions.

### Total Kjeldahl Nitrogen (TKN)

The samples were digested with a solution containing sulfuric acid, potassium sulfate, and mercuric sulfate converting organic nitrogen to ammonium sulfate. The digested samples were steam-distilled into a saturated boric acid solution and titrated with standard hydrochloric acid.

### Total Phosphorus (TP)

The samples were digested in concentrated HNO<sub>3</sub> and

evaporated to dryness; concentrated  $\text{H}_2\text{SO}_4$  was added and heated until the solution cleared. Water was added and the samples were filtered through a glass filter. The filtrates were analyzed for total phosphorus by the single solution method, using ascorbic acid as the reducing agent. The developed samples were read on a Klett-Summerson Photoelectric colorimeter, model 900-3.

#### Metals (Cd, Cu, Zn and Pb)

One gram of sample was heated to fuming with ten milliliters of concentrated  $\text{HNO}_3$  acid. After cooling, ten additional milliliters of acid were added, heated and cooled. The samples were centrifuged and the supernatants measured for volume and analyzed on a Varian Atomic Absorption Spectrophotometer, model AA-5.

#### Mercury (Hg)

The samples were digested with concentrated  $\text{H}_2\text{SO}_4$  overnight. The digested samples were oxidized with 5 percent  $\text{KMnO}_4$  and transferred to 300 ml BOD bottles. After the addition of reductant solution the BOD bottles were immediately attached to the aeration apparatus of a Coleman Mercury Analyzer MAS-50. Mercury concentrations were determined from standard curves. The composition of reductant solution is as follows:

|                                       |                 |
|---------------------------------------|-----------------|
| $\text{H}_2\text{O}$                  | 600 ml          |
| $\text{H}_2\text{SO}_3$               | 100 ml          |
| $\text{NaCl}$                         | 5 grams         |
| $(\text{NH}_2\text{OH})_2\text{SO}_4$ | 20 grams        |
|                                       | q.s. to 1 liter |

## Oil and Grease (O & G)

The sediment samples were dried with magnesium sulfate monohydrate, the soxhlet-extracted with hexane (Standard Methods for the Examinations of Water and Wastewater, 12th Ed., APHA, Inc., N.Y., 1965; 531-532). The hexane was then evaporated to dryness. The weight of solid residue from the solvent evaporation yields oil and grease.

Appendix II. Design curves for boats drafts for establishing minimum dredging depths from Adie (1975).

